Everything you want to know about the world we live in

NEW

HOW IT WORKS
Annual

1000s OF AMAZING FACTS INSIDE

Digital Edition

VOLUME 10

SCIENCE | ENVIRONMENT | TECHNOLOGY | TRANSPORT | HISTORY | SPACE

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Welcome to the tenth volume of the How It Works Annual, where your burning questions about how the world ticks finally get answered. Feed your mind, indulge your curiosity and uncover the truth behind some of the most popular misconceptions. We delve deep into the mysteries of our world with in-depth and entertaining articles, accompanied by cutaways, illustrations and incredible images to show you exactly what goes on inside. The How It Works Annual explores the universe through six areas of knowledge: technology, transport, the environment, history, science and space. Our subjects range from the dinosaurs and meteor showers to the future of technology and the greatest engineering feats of the modern world. In this edition, you'll also find a special feature on humankind's efforts to recreate the Sun's immense power on Earth. We've also got features on the devastating Chernobyl disaster, the robots who will soon play a key role in warfare and the gigantic new sewer system currently being excavated below the busy streets of London.

Ready to learn more about the astounding world around you? Then read on and be amazed.

HOW IT WORKS Annual

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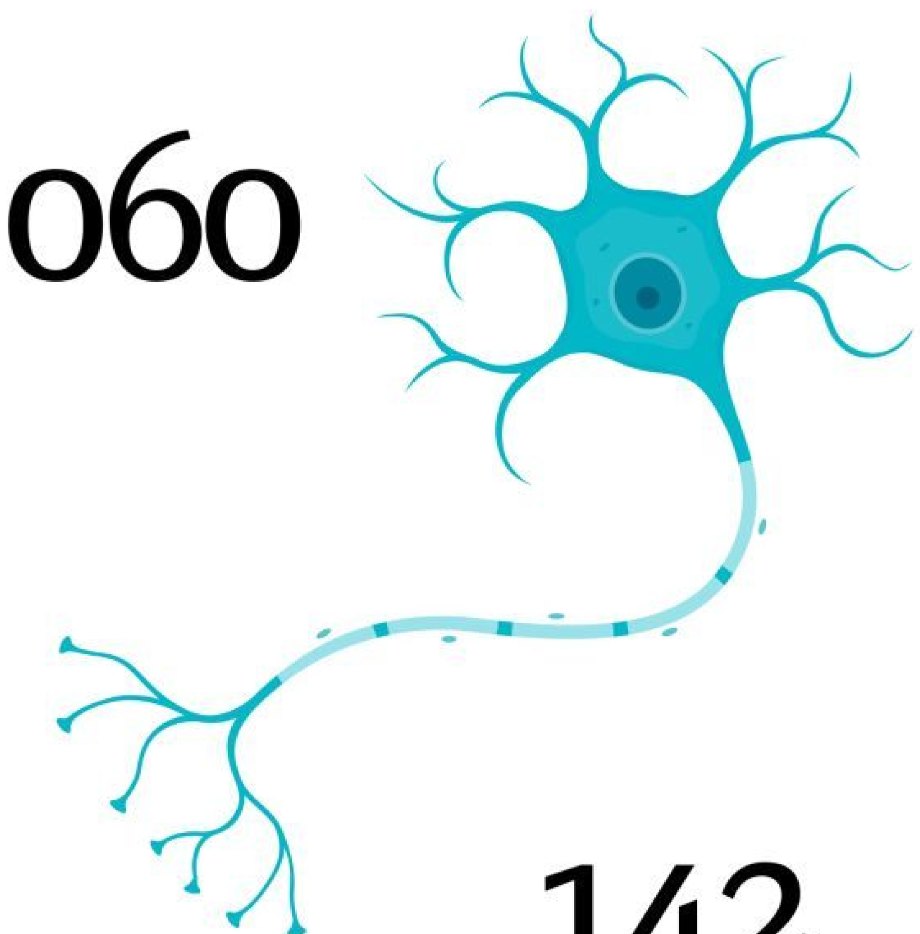

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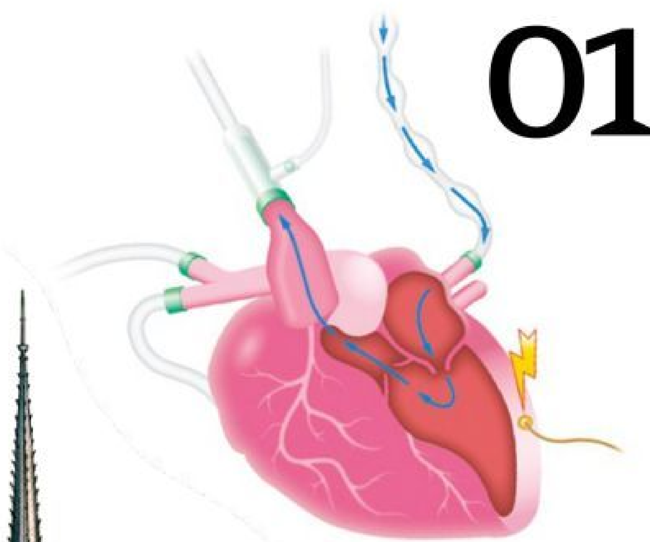

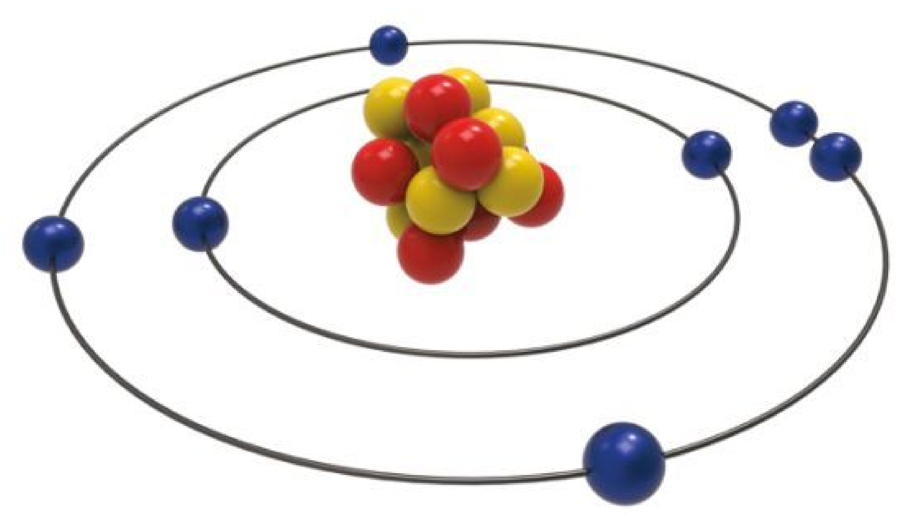

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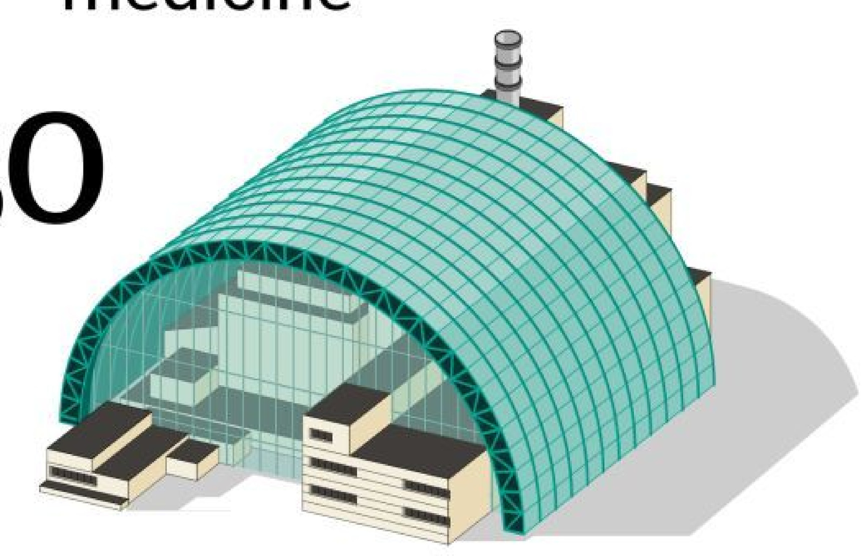

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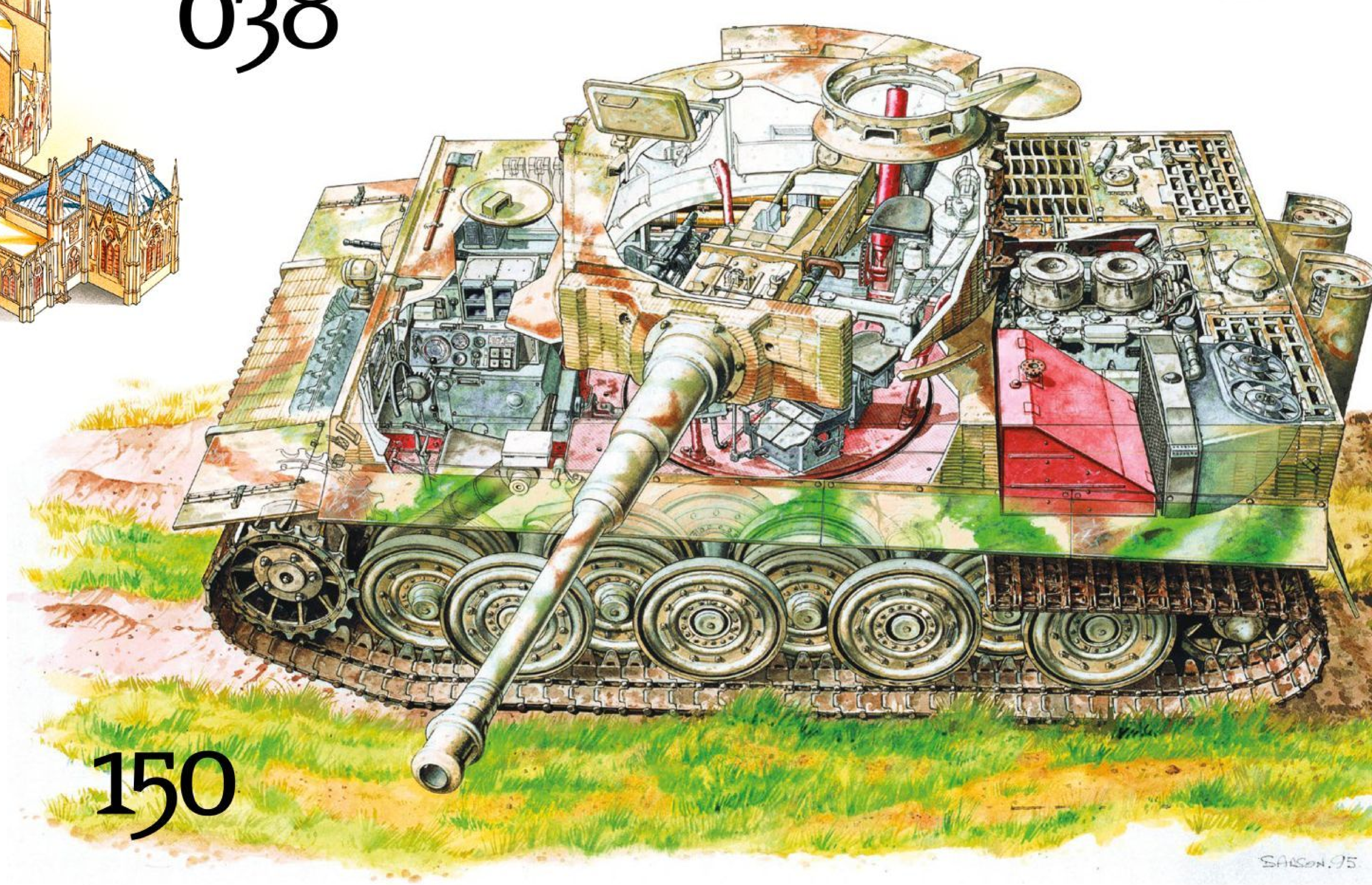

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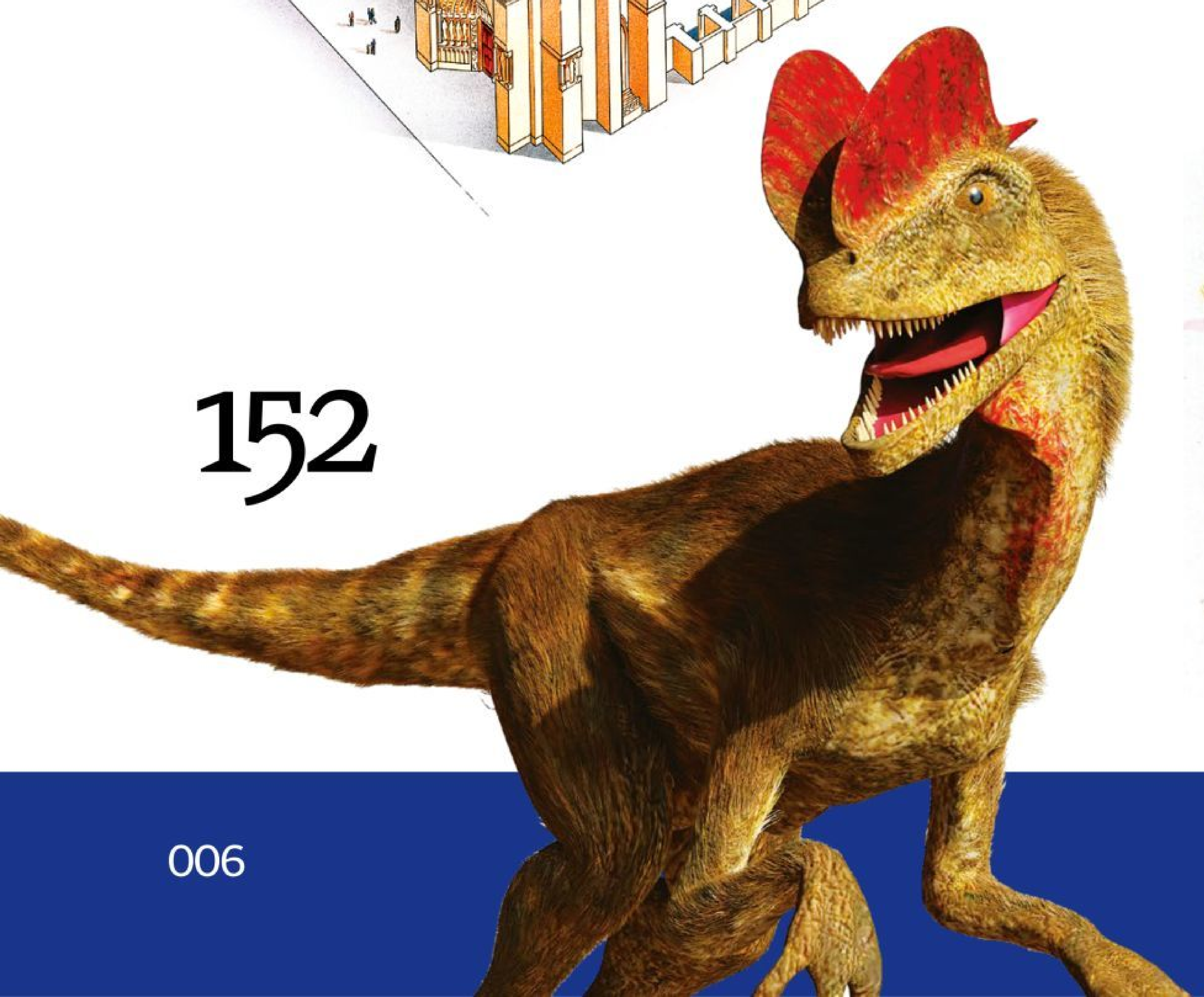

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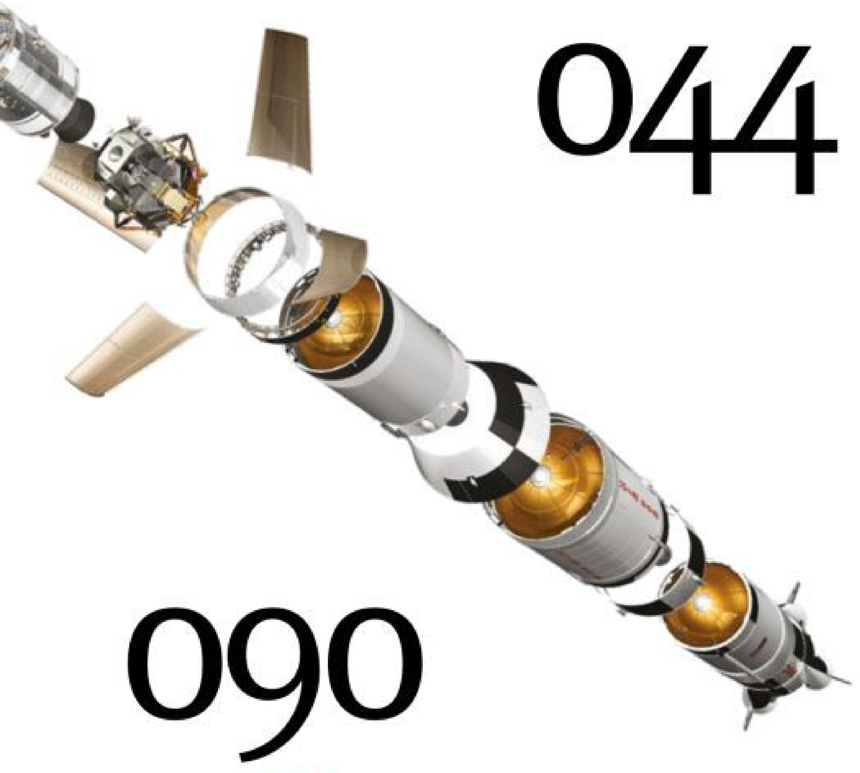

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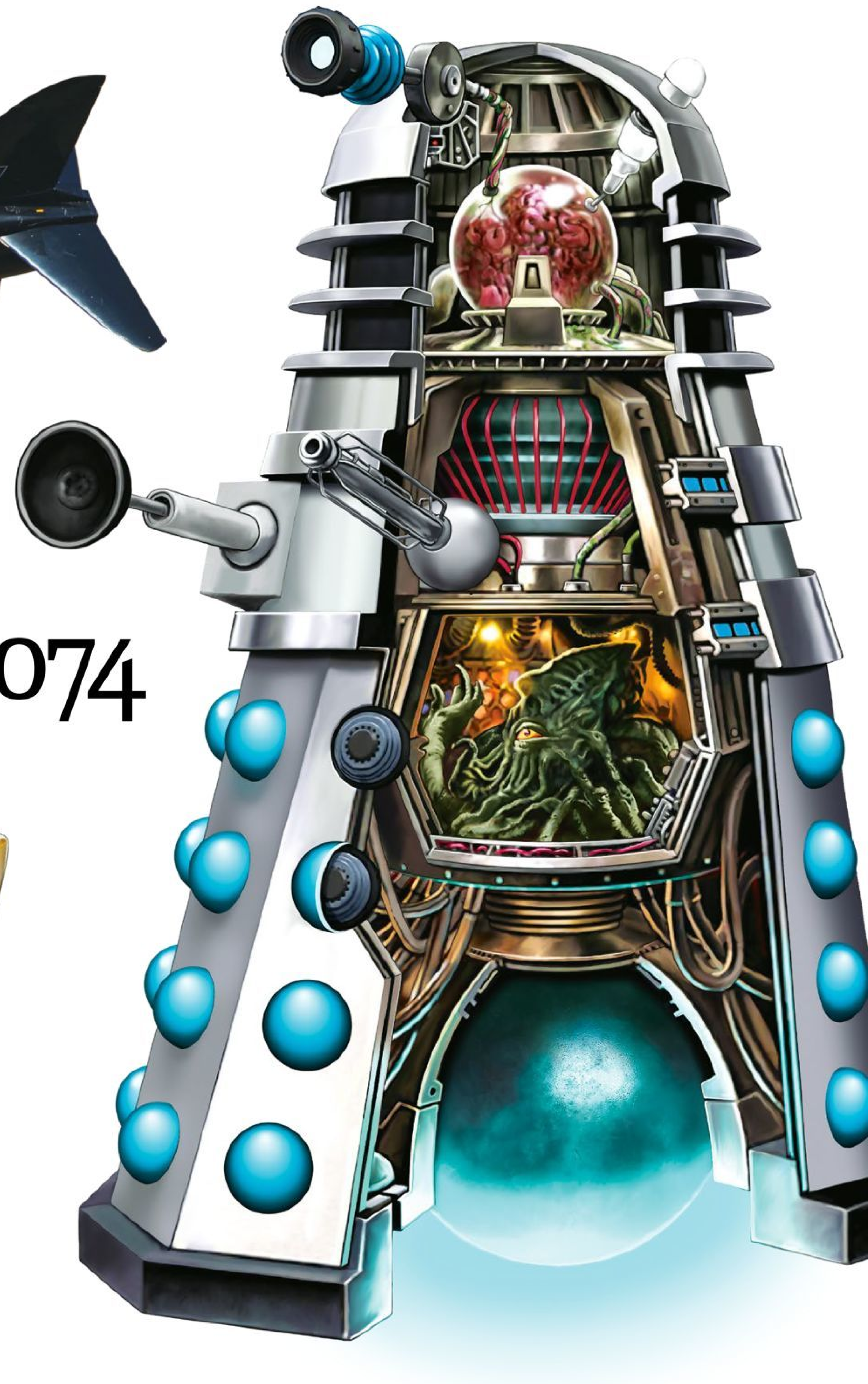

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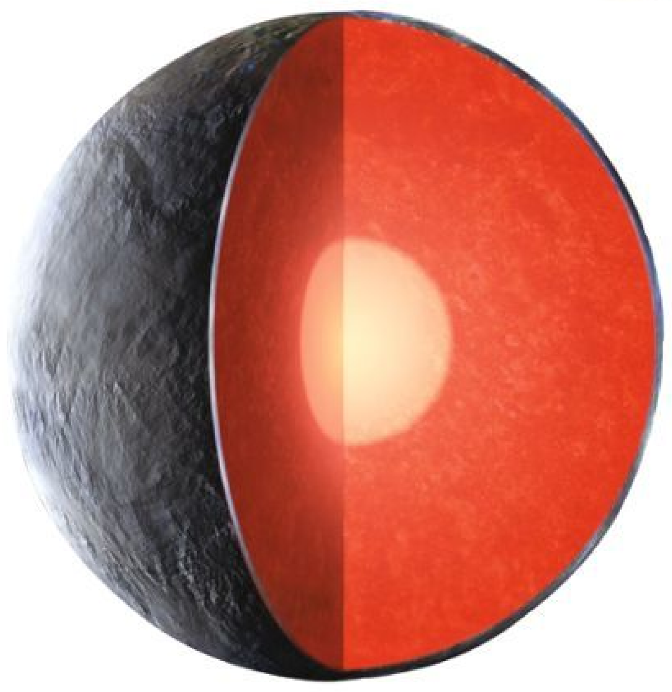

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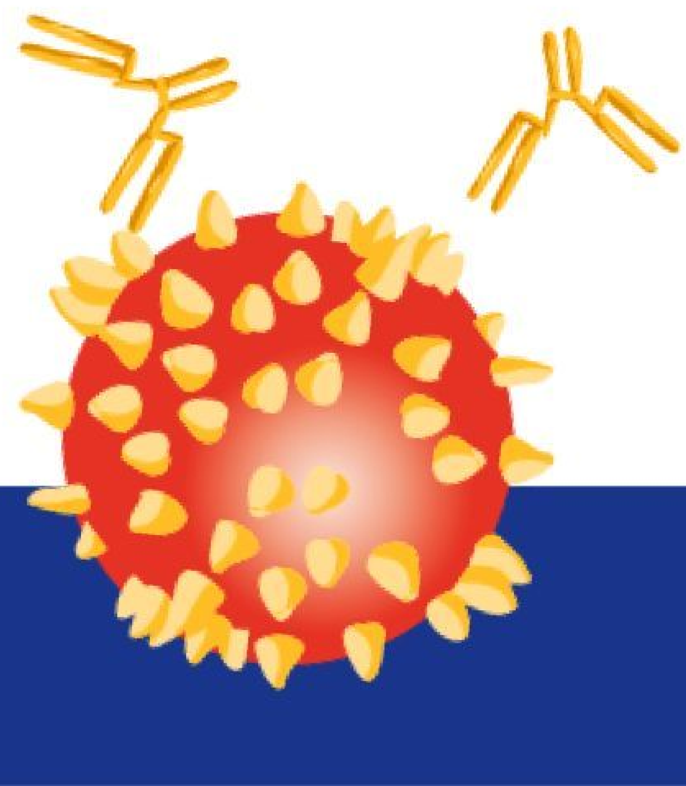

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C FRONT 90
FACE "F"
AS SHOWN

POWER OF THE SUN

Our star is the heartbeat that keeps Earth alive. Can we recreate this fundamental energy source on Earth?

Words by **Laura Mears**

The Sun is the powerhouse of the Solar System, and this giant fusion reactor is vital to life on Earth. Almost every organism on the planet owes its life to our nearest star. Its stellar pulse depends upon the smallest and lightest element in the universe – hydrogen – and a reaction called the proton-proton chain.

Hydrogen atoms are as simple as they come. The basic version has one positively charged proton for a nucleus, orbited by one negatively charged electron. Normally, atoms keep their distance from one another; the positive charges inside their nuclei repel, like magnets. But at the heart of the Sun, the temperature and pressure is intense. The atoms there move so quickly that they slam through the repulsive nuclear forces, colliding at high speed. When these collisions happen, the nuclei can get stuck together.

Nuclear fusion takes place in stages, starting with a collision between two protons. When this collision happens, one proton spits out a positron (a positively charged electron) and a neutrino (an electron with no charge). With these two particles missing, one proton becomes a neutron, and the pair form a heavier isotope of hydrogen called deuterium.

The next stage happens when that deuterium hits another proton. This fusion releases a burst of gamma radiation and creates a new type of atom – a light version of helium called helium-3. Now carrying two protons and one neutron, this atom is ready for the final stage of the fusion process.

When two helium-3 atoms collide, they fuse to make an alpha particle (helium-4). This particle contains two protons and two neutrons (like a normal helium nucleus). The remaining two protons shoot away, ready to go through the cycle again.

But how does this create energy? To understand the power of the Sun, we need to

delve into the equations of one of the greatest scientists who ever lived: Albert Einstein. In his theory of special relativity, Einstein explained that mass and energy are the same, and one can become the other. His famous equation, $E = mc^2$, describes their relationship. The energy (E) of an object is equal to its mass (m) multiplied by the square of the speed of light (c). This is the relationship that powers the nuclear reactor at the heart of our star.

The helium nuclei the Sun produces have less mass than the hydrogen nuclei that made them. When the atoms slam together, a tiny proportion of their mass (less than one per cent) escapes. Less than one per cent might sound tiny, but a quick look back at Einstein's equation explains how nuclear fusion produces so much power. The speed of light is 299,792,458 metres per second, so it only takes a tiny release of mass to let out a huge amount of energy.

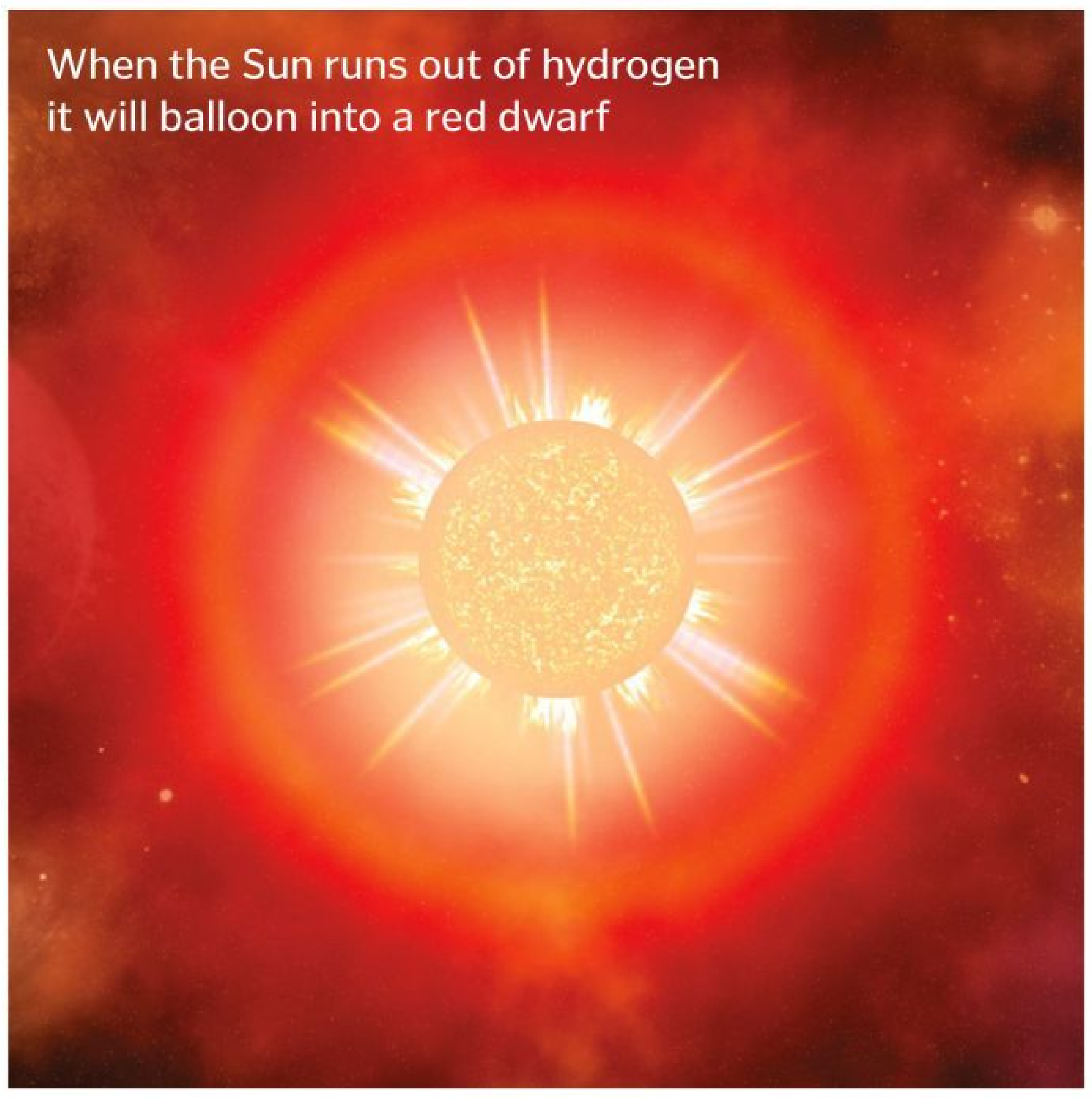
The hydrogen bomb 'Ivy Mike' triggered nuclear fusion on Earth for the first time

The Sun has been converting mass into energy for more than 4 billion years, and it's already burnt through a lot of fuel. If you looked into the core today, you'd find that around 62 per cent of the hydrogen nuclei have already fused to become helium. However, there's a lot of hydrogen left and the process happens slowly, which is lucky for us, because almost all life on Earth depends upon the Sun for survival.

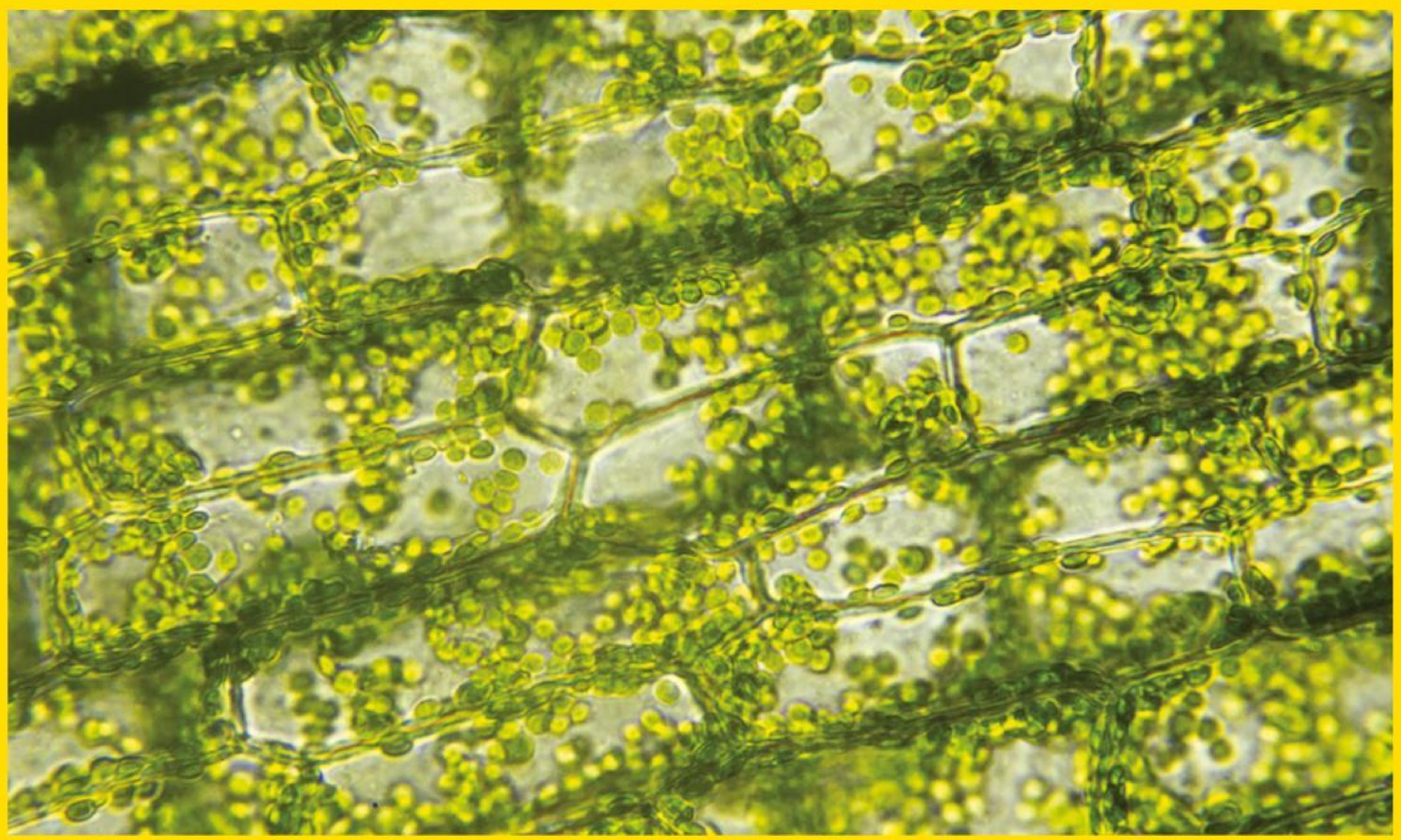
> "The Sun has been converting mass into energy for more than 4 billion years"

Though we don't yet know exactly how life evolved, we know that the Sun played an important role. Before life, Earth had no oxygen in its atmosphere. The air was a thick fog of carbon dioxide, methane and sulphurous gases venting out from the molten rocks. Life emerged around 3.8 billion years ago, probably in hot vents deep under the sea.

A few types of modern microbe still live in these strange environments, including bacteria called acetogens and archaea called methanogens. They harvest chemicals from Earth's rocks, strip electrons away and use the energy to break the oxygen out of carbon dioxide. This enables them to make organic molecules like acetate and methane, and energy-carrier molecules like ATP. The trouble with these reactions is that they don't make that much energy. For life to boom on Earth, organisms needed a better way to power their



When the Sun runs out of hydrogen it will balloon into a red dwarf



The tiny green chloroplasts that power these cells used to be free-living bacteria

Converting sunlight into food

Plants trap the Sun's power in two high-energy molecules, NADPH and ATP, before releasing it again to make sugar and oxygen. The process begins with two lower-energy molecules, NADP+ and ADP, and two types of chlorophyll, P680 and P700.

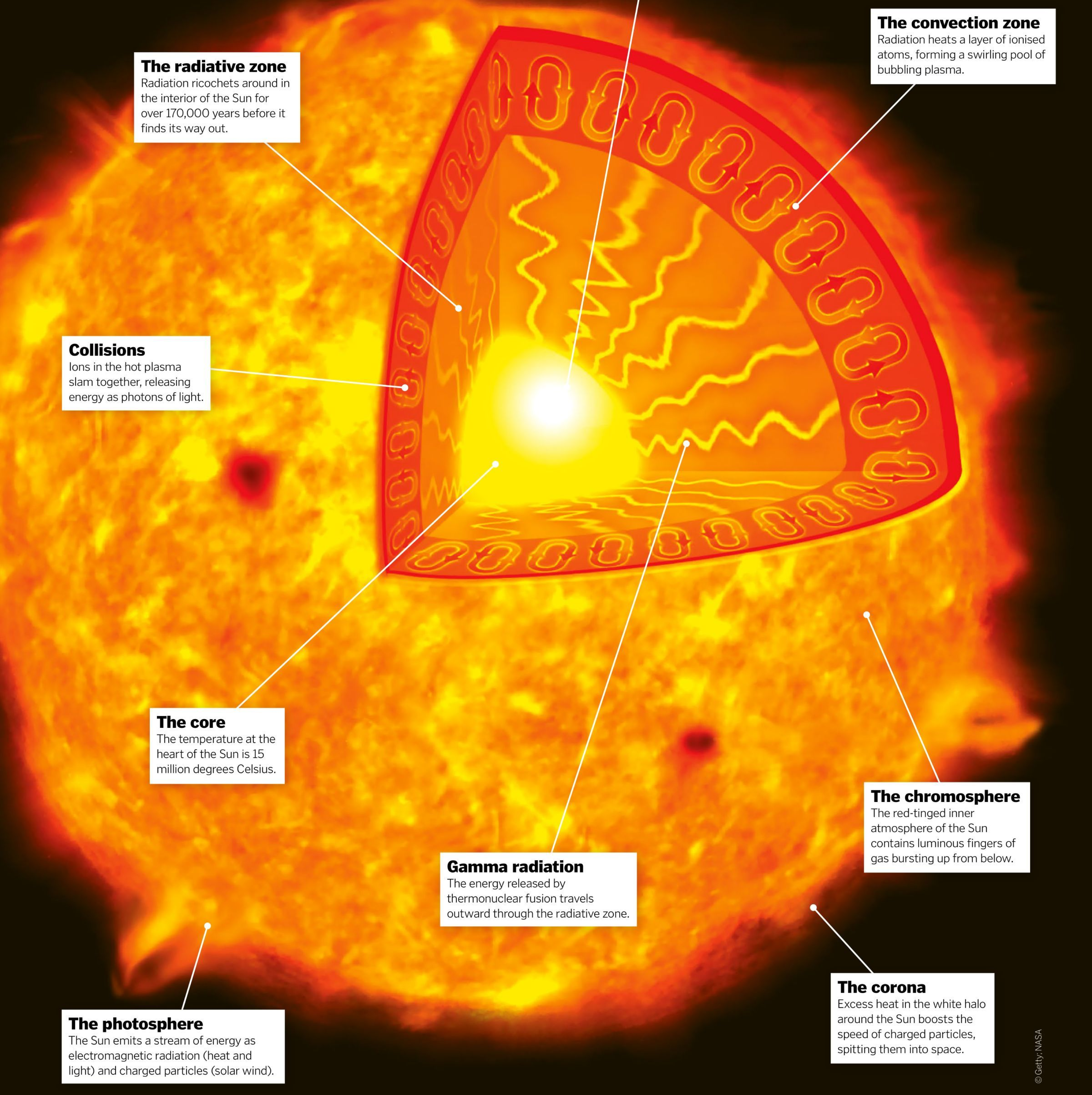
The chlorophylls work together with other pigments to capture photons of light. P680 goes first, absorbing a photon and spitting out an electron. The electron passes into a transport chain, releasing energy as it moves from link to link. This energy powers the production of ATP.

At the end of the chain, the electrons reach P700, which absorbs its own photon and passes the electrons into a second transport chain. This time, they power the production of NADPH.

The NADPH and ATP molecules go on to power a series of chemical reactions called the Calvin cycle. The cycle combines carbon dioxide with hydrogen ions to make sugar, providing the building blocks that keep life on Earth alive.

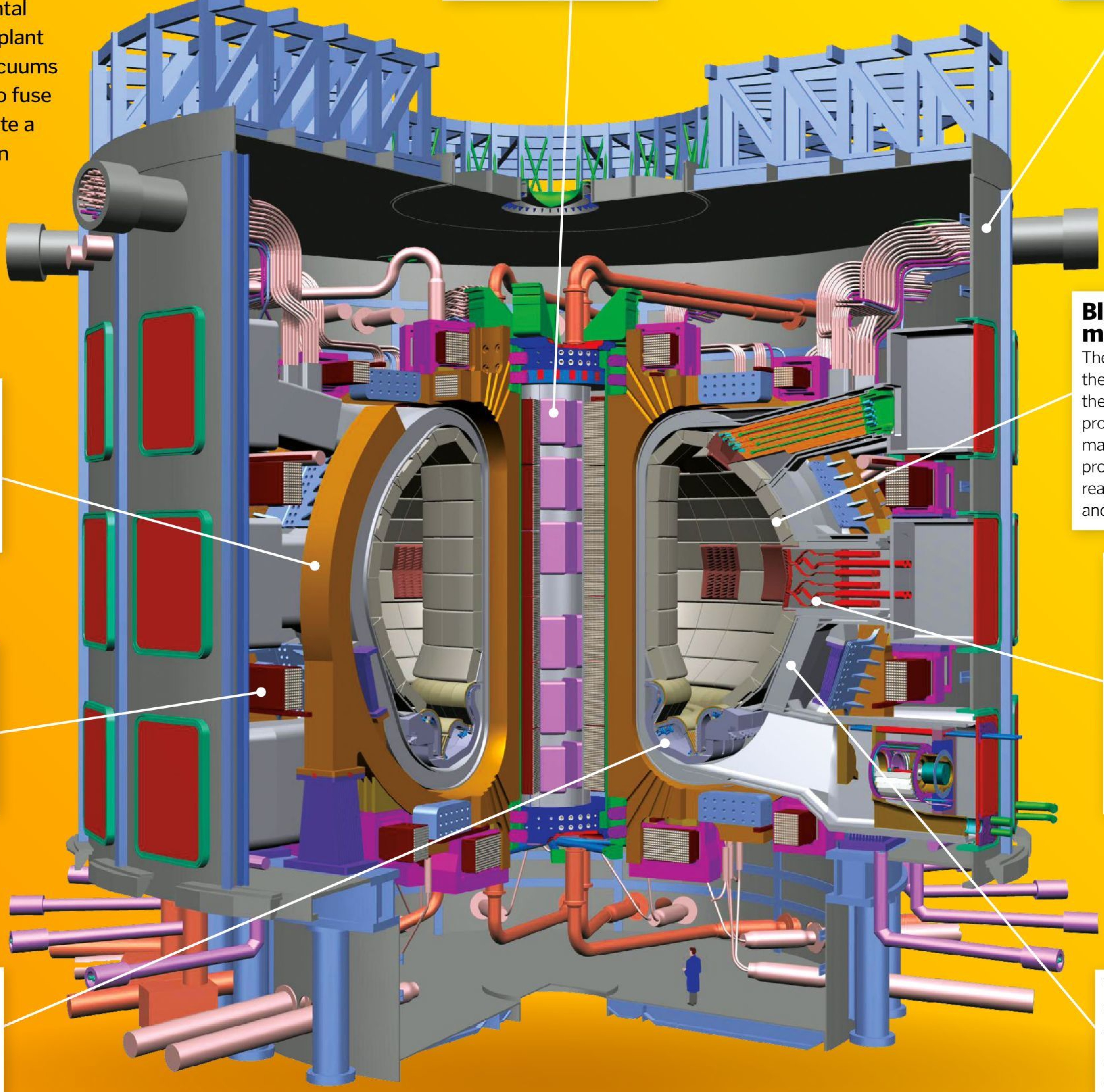
HOW THE SUN CREATES ENERGY

Inside the Sun's nuclear reactor is a massive matter-to-energy converter



A STAR IS BORN

The experimental tokamak power plant uses magnets, vacuums and hot plasma to fuse atoms and create a synthetic Sun



Magnetic field
When the central magnet switches on, it induces a powerful magnetic field in the plasma ring.

Insulation
A steel shell encases the system in a vacuum, keeping the temperature cool.

Blanket modules
These shields coat the inner surface of the vacuum vessel, protecting the magnets from the products of fusion reactions – heat and stray neutrons.

Doughnut magnets
Toroidal field coils keep the plasma under control by forcing it into a doughnut shape.

Particle cannon
The Ion cyclotron system accelerates beams of particles and fires them at the plasma, heating it up.

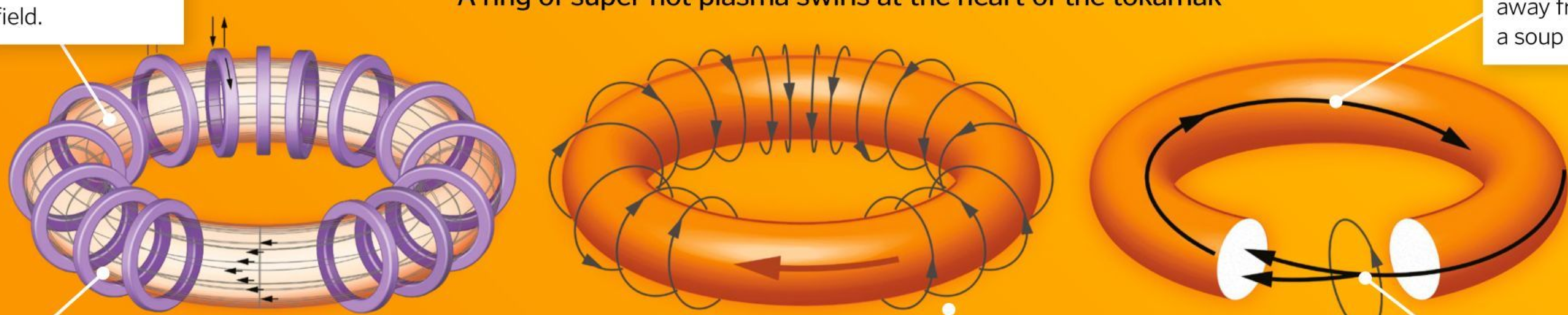
Plasma protection
Ring-shaped magnets keep the plasma away from the walls of the vacuum vessel.

Divertor
The waste-disposal system sits under the vacuum chamber, removing heat and ash.

Vacuum vessel
This sealed, air-free chamber contains the ring of plasma.

CREATING CURRENTS

A ring of super-hot plasma swirls at the heart of the tokamak



Magnetic cage
A constant current through the toroidal magnets creates a doughnut-shaped magnetic field.

Plasma
In this high-energy state of matter, electrons break away from atoms, creating a soup of charged particles.

Containment
The magnetic field interacts with the charged particles in the plasma, trapping them inside the ring.

Transient fields
Pulses from the poloidal magnets induce a current in the plasma, creating magnetic fields that pass around the doughnut.

Stirring the soup
The fields from the toroidal magnets interact with the fields from the poloidal magnets, twisting the plasma current.

chemistry. Enter the phototrophs. These organisms use the energy from light to break into chemical bonds.

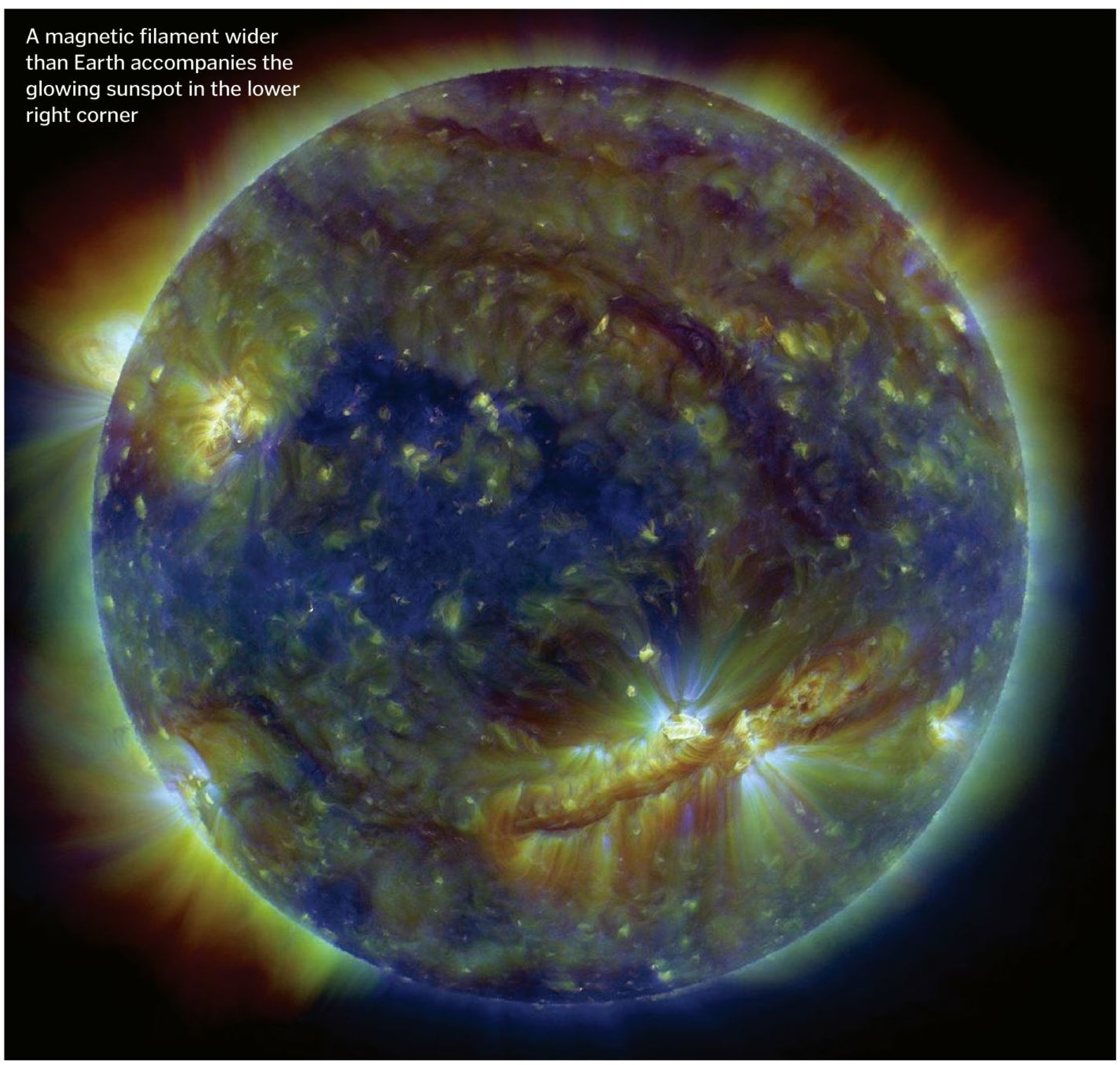
The most famous phototrophs are, of course, plants. Plant cells contain dozens of chloroplasts, each stuffed with discs called thylakoids. The thylakoids house molecular machines called photosystems, which contain chlorophyll pigments. These capture photons of light from the Sun, harnessing their energy.

Evolving the ability to make chlorophyll is so complicated that scientists think it happened only once. This means that every organism that uses chlorophyll must have come from the same ancestor – photosynthetic cyanobacteria that lived more than 2.15 billion years ago. These strange cells were able to make food and oxygen from light, and other cells wanted to get in on the action. Larger cells started to live alongside the bacteria, sharing their resources. The relationship became so close that the larger cells eventually absorbed the smaller ones. The two types of cell evolved together, and the bacteria lost the ability to live on their own, becoming the chloroplasts we see in plant cells today. Photosynthesis now provides the raw materials for almost every food web on the planet.

Sun-powered evolution changed Earth, but while we've been busy adapting to sunlight, the Sun has been changing too. It's been fusing hydrogen for 4.5 billion years, and in that time it's been getting brighter. For every four hydrogen atoms that it fuses to make a helium nucleus, the mass inside its core drops. There are now far fewer atoms in the centre of the star, and this means that there are fewer particles to balance gravity pulling inwards and the gas pressure pushing outward.

This causes the Sun's core to contract, which causes the remaining particles to heat up, and in turn speed up nuclear reactions and make the Sun brighter. As this happens, the gas around the outside of the Sun expands. Over the last 4 billion years it has become around 20 per cent bigger, and it is still growing.

On shorter timescales, the power output of the Sun has been fluctuating too. Its atmosphere is stormy, and magnetic activity below the surface creates solar weather in the form of sunspots. They start out near the Sun's poles and move towards the equator, growing to planet-sized magnetic swirls. In the early 1800s, William Herschel noticed that when the number of sunspots dropped, the price of wheat rose. The weather on the surface of the Sun coincided with a period of drought on Earth; it seemed to affect the weather here. People started to track sunspots and noticed cyclical patterns: every 11



A magnetic filament wider than Earth accompanies the glowing sunspot in the lower right corner

Countdown to fusion power

Can TAE Technologies plug a fusion powerplant into the grid by 2023?

1998

Development and testing of the science begins, leading to more than 800 patents

2009

Construction of a full-scale machine is completed and equipment testing begins

2013

The system is upgraded with a powerful plasma injector, built by the Budker Institute of Nuclear Physics, Russia

2015

The temperature in the reactor reaches 10 million degrees Celsius – for full fusion, it needs to reach 3 billion degrees Celsius

2018

After 4,000 experiments, the system nearly reaches 20 million degrees Celsius

2023

The target temperature will be reached, the technology will be licensed and construction of fusion power plants will begin

"Photosynthesis provides the raw materials for almost every food web on the planet"

years, the number of sunspots rises and then falls again.

We still don't know why this solar cycle is 11 years long, but it could be to do with the dynamo effect inside the star. The Sun's convection zone contains a soup of charged particles called plasma. These particles are in constant motion, heated from below and swirled by the Sun's rotation. This creates powerful currents that set up toroidal (rings that follow the lines of latitude) and poloidal (rings that follow the poles) magnetic fields.

At different points in the solar cycle the fields change in strength, which changes the way they interact, altering the sunspots on the surface. The variations in the Sun's output across the cycle are small, but sometimes they add up to big changes on Earth. In the 16th century through to the mid-19th century, as the number of sunspots dipped, the world plunged into the Little Ice Age.

Ice ages pale into insignificance when compared to what's to come. The Sun is about halfway through its life and, as it ages, its output is set to change dramatically. When it runs out of hydrogen in its core, it will start to use the hydrogen in the shell outside. Helium will continue to accumulate beneath, and as the core gets bigger the Sun will start to swell. It will grow brighter and hotter and the fusion reactions will proceed faster and faster, until it burns more than two times as fiercely as it does today. This will scorch the surface of the Earth, raising the temperature to more than 300 degrees Celsius.

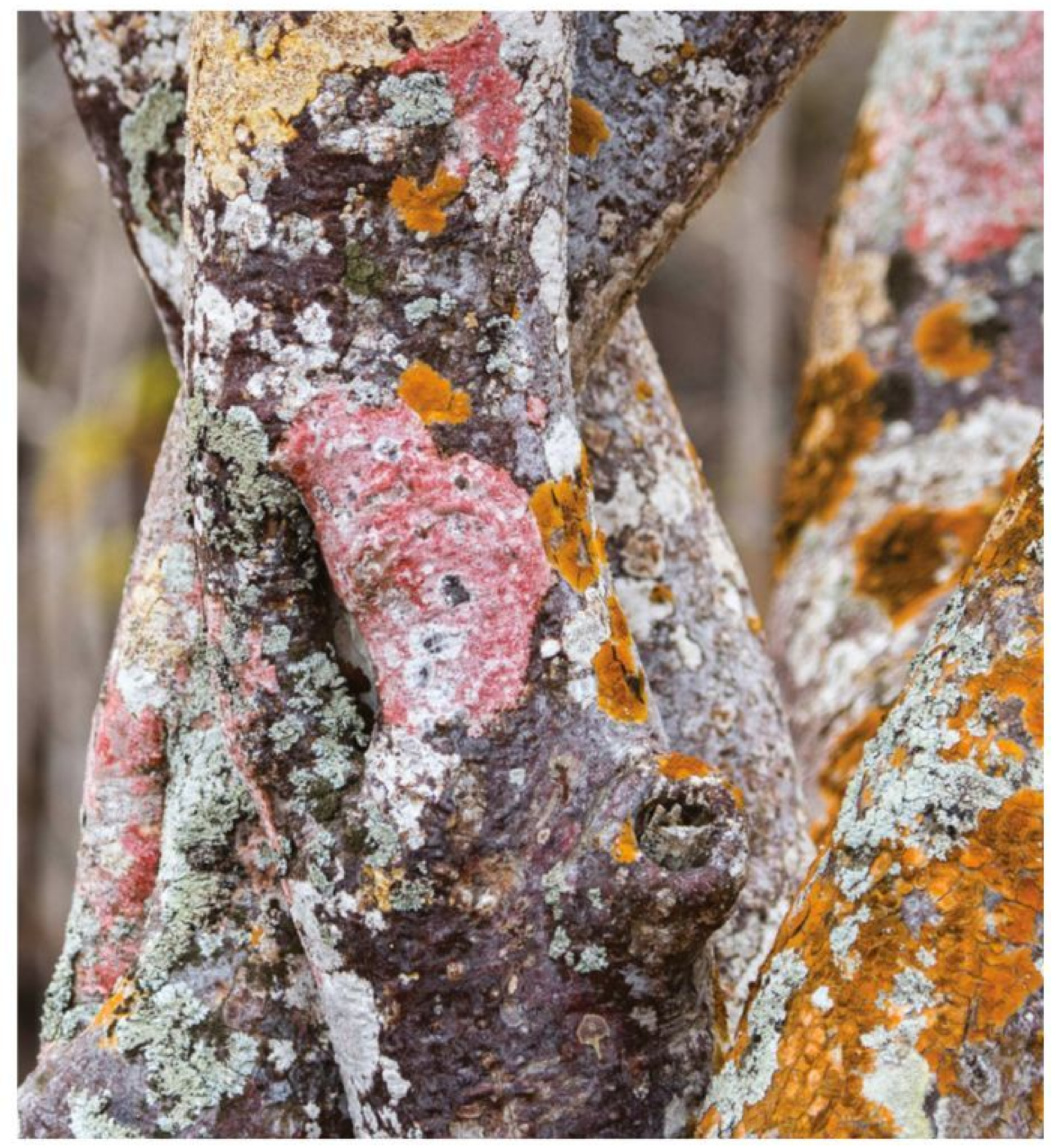
Eventually the hydrogen will run out. Then, the Sun will ignite in a helium flash and its core will start to fuse helium nuclei, transforming them into heavier elements like carbon and oxygen. In the process, the Sun's outer layers will swell, and it will become a red giant, 34 -imes brighter than it is now.

The Sun will swallow Mercury and Venus, and Earth's surface will melt into pools of molten metal. By this time, the Sun will be hundreds of times brighter and hotter than it is today, and Earth's rocks will start to boil away.

When all the helium is gone, the Sun's fusion reactor will switch off. Its outer layers will cool and its atoms will blow away into space, forming a swirling planetary nebula and a white-hot core. This core, a white dwarf, will eventually cool until it is a dead, black cinder, and the light in our Solar System will go out forever.

This is how the Earth may appear as the Sun expands towards the end of its life

> "The Sun will swallow Mercury and Venus, and Earth's surface will melt into pools of molten metal"



Lichens form when algae and bacteria capture energy from the Sun and share it with fungi

LIFE IN THE SHADOWS

Where, in Earth's darkest places, do microbes make their energy independently of the Sun?

Hydrothermal vents

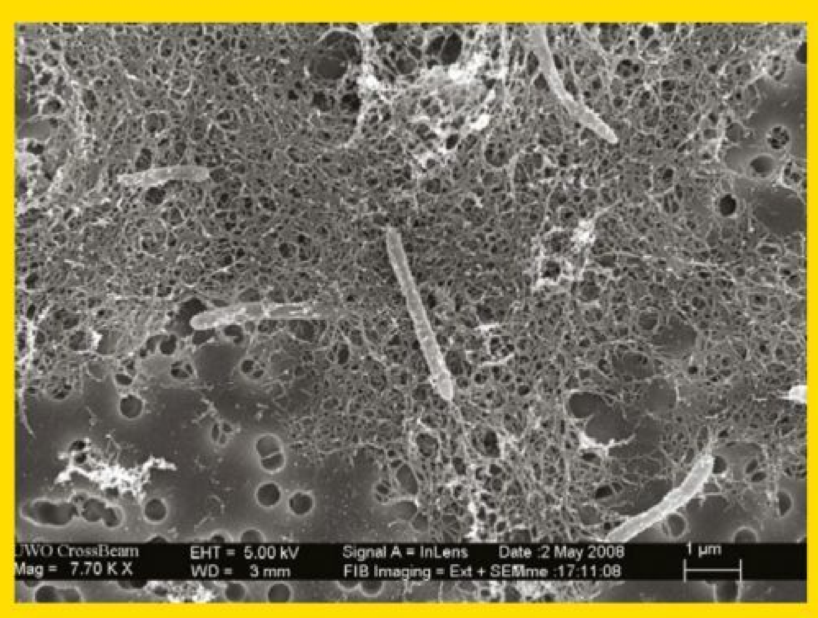
RIFTS IN THE OCEAN FLOOR

Some organisms have discovered a way to make energy from the hydrogen sulphide that leaks out from hot volcanic vents under the sea. Microbes combine hydrogen sulphide with water and carbon dioxide to make sulphur and glucose. Giant tube worms then store the microbes and use their waste to stay alive in the dark.

Methane seeps

CRACKS IN EARTH'S CRUST

Cold seeps can also sustain life without sunlight. These seafloor biomes leak bubbles of methane and hydrogen sulphide into the water, which can then feed colonies of bacteria. The bacteria form mats on the ocean floor, and they can provide enough energy to sustain beds of mussels and also groups of tube worms.



Volcanic rocks

THE CREVICES BETWEEN GOLD MINE ROCKS

The gold mine bacteria *Desulforudis audaxviator* lives in total darkness, nearly three kilometres below South Africa's surface. It survives at temperatures above 60°C with nothing but rocks to eat. It gets power from the radioactive decay of uranium and is able to extract carbon and nitrogen from the rocks.

Under Antarctic ice

BENEATH POLAR ICE SHEETS

Rock-eating microbes found 0.8 kilometres below the surface of an Antarctic ice sheet may also be able to survive without the Sun. Like their cousins in the hot hydrothermal vents, these microbes extract energy from compounds containing sulphur and also iron. But temperatures in this environment here are below freezing.

LET THERE BE LIGHT

The Sun is the powerhouse of the Solar System. So let these impressive facts enlighten you

91%
Proportion of atoms that are hydrogen

1 H 1.008

70.6%
Proportion of mass that is hydrogen

5,500 degrees Celsius
Temperature at the surface

3.8×10^{26} Watts
Power output every second

150 million kilometres
Distance between the Sun and Earth

2 million degrees Celsius
Temperature of the Sun's atmosphere

1,391,016 kilometres
Diameter at the equator

600 million tons
Hydrogen used up every second

5 billion years
Until the helium-burning process begins

15 million degrees Celsius
Temperature at the core

SCIENCE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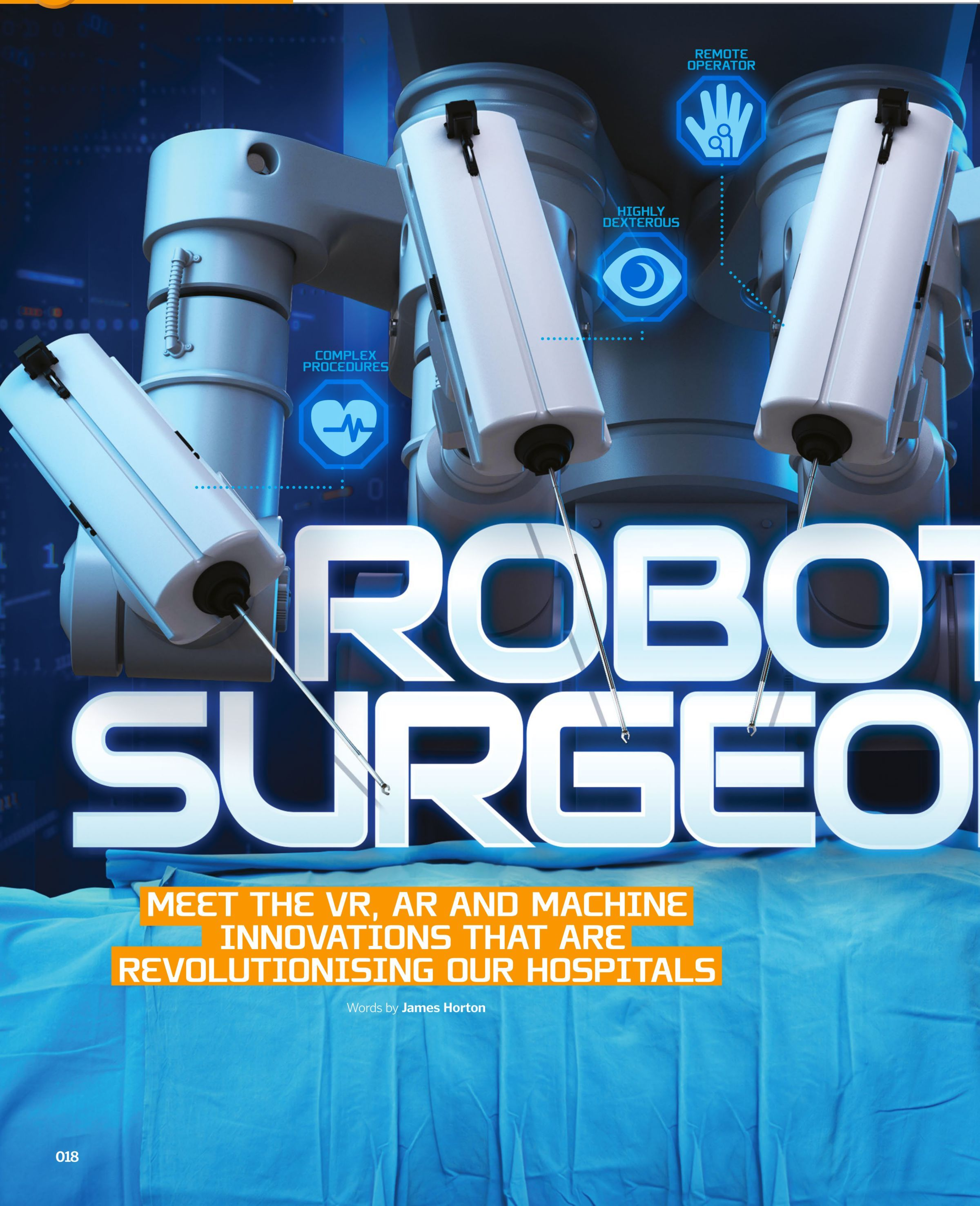
The Chernobyl disaster


028
How we taste


038
Atom anatomy



ROBOT SURGEO

MEET THE VR, AR AND MACHINE INNOVATIONS THAT ARE REVOLUTIONISING OUR HOSPITALS

Words by **James Horton**

The field of surgery perhaps relies more on technological innovation than any other medical practice. Yet during the Neolithic period, the final era of the Stone Age, surgery was already taking place. Trephining – where a hole would be made into the skull – was used as a proposed treatment for an ailment that still remains a mystery to us today – although the ancient Egyptians would later use the same procedure to treat migraines. Remarkably, some individuals survived this treatment long enough to undergo it a second time!

As with many things in the Western world, our understanding of surgery was bolstered by the ancient Greeks, who performed autopsies to learn about anatomy and helped the living by setting broken bones, 'bleeding' their patients, performing amputations and even draining fluid from lungs. The advanced Islamic world of circa 900 CE would go on to produce books on ear, nose and throat surgery and several other subjects. But without anaesthetic, antiseptics and advanced equipment, these practices remained extremely dangerous and an understandably terrifying prospect for a patient.

By the Middle Ages Europeans had at least made tentative advances in anaesthetics. Unfortunately, the concentrations of herbs and alcohol used for this purpose were about as dangerous as the surgery. They were so powerful that many patients died on the operating table before the surgeon had even started the procedure. Surgeons of this time were an interesting group, as they were mostly barbers by trade; these barber-surgeons would pull a tooth, set a bone or even perform an amputation if the need arose.

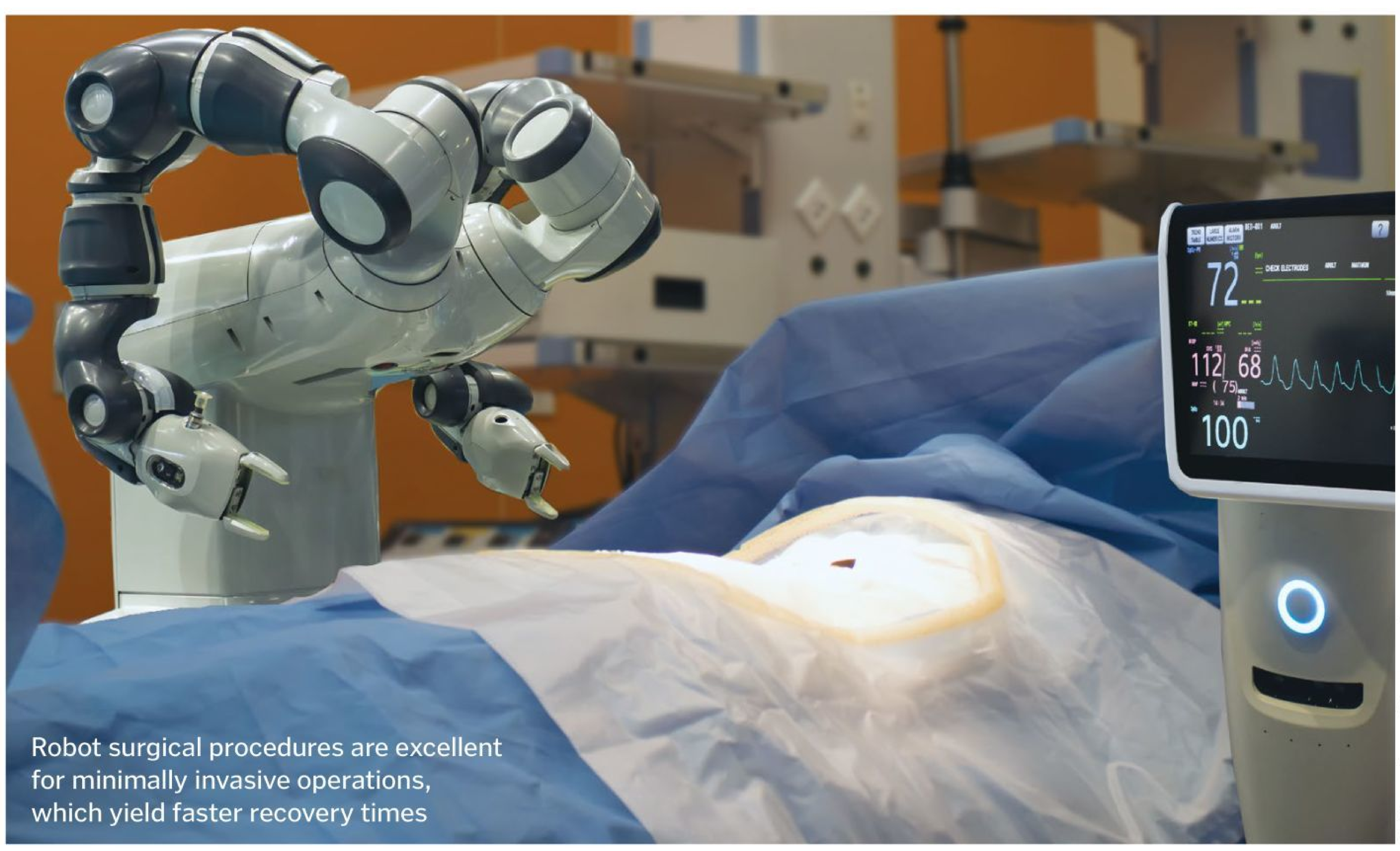
It would take until the 1800s, once the Age of Enlightenment had driven new innovations in science and technology, for an anaesthetic gas to find widespread use. Later that same century we also came to understand germ theory and how to prevent infection following surgery – the basis of modern infection control.

This exponential progress would continue into the 20th century as antibiotics, blood transfusions and X-rays would all increase the safety and effectiveness of surgery. By the turn of the millennium, with our then-comprehensive knowledge of surgery, it would have been easy to believe that little potential remained for future progress. By then people were not only undergoing routine surgery for life-saving operations but also to improve their quality of life, or even just for cosmetic purposes. But it seems we were still just getting started.

Advances in software development and robotics hold immense promise for revolutionising surgery, and many are already making their way into the clinic. These technologies will be found in nearly every corner of the surgical practice, from training future surgeons to conducting a complex procedure.

Let's start at the beginning. Imagine you're a budding surgeon who's itching to get some insight into your chosen profession. The standard process for this would have you peering over an experienced surgeon's shoulder, sometimes travelling far afield to visit an expert based at a distant hospital. But in 2016 VR

"Advances in software development and robotics hold immense promise for surgery"



Robot surgical procedures are excellent for minimally invasive operations, which yield faster recovery times

(virtual reality) was first revealed to be an amazing technology for sharing an immersive view of a surgeon's work in real time. Surgeon Shafi Ahmed performed a live, 360-degree broadcast of a tumour-removal operation. Unlike video footage, VR enables surgical tutees to survey their surroundings, check in on other members of the surgical team and begin to imagine themselves filling the practising surgeon's shoes.

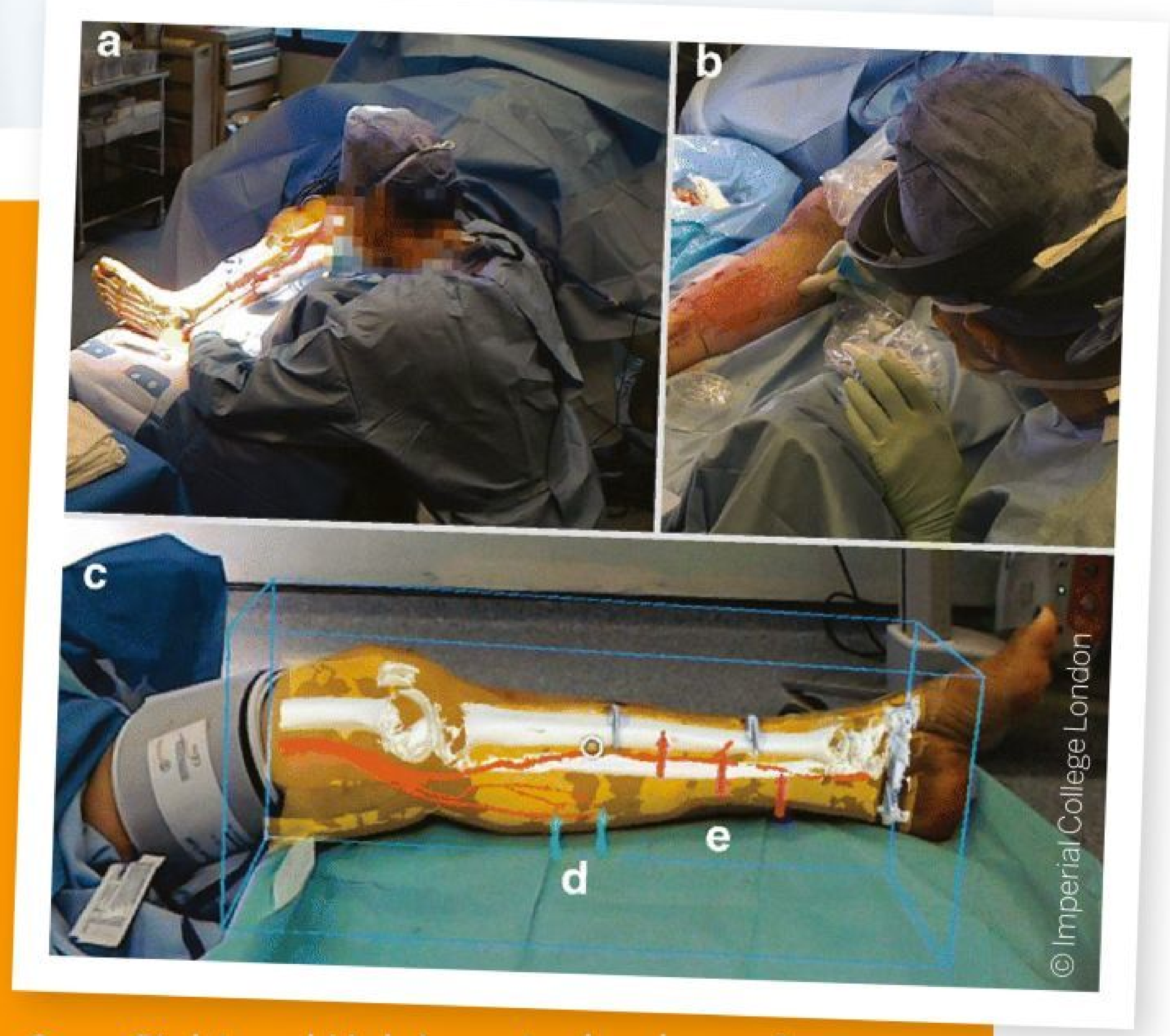
With theoretical knowledge sufficiently enhanced, the next step in your next-generation surgical training would be practice. Of course, practising surgery can be a risk-laden affair, but advanced 3D printing can provide much of the benefit with none of the risk. Physicians at the University of Rochester Medical Center, New York, successfully converted medical scans into computer-generated designs to print artificial organs that look, feel and bleed like organs and have the same mechanical properties. The aim is for these to enable aspiring surgeons to hone their skills to a high standard before beginning on actual patients. Plus, as an added benefit, 3D-printed models can be used for pre-planning and rehearsing complicated surgeries beforehand, increasing the chance of their success, even by experienced surgeons.

Imagine you're now a surgeon and we fast-forward to a day in your operating theatre: you are attempting a complicated procedure, where accurate incisions and expert guidance are paramount. Fortunately, you've graduated from virtual environments to augmented environments, and through your high-tech specs you can see the patient's internal structures mapped onto their body. An external expert from across the globe can see this too, and they are offering advice as you conduct the surgery. This augmented reality prospect, which has been championed by Microsoft's HoloLens

Virtual reality will play a role in training the surgeons of tomorrow

Seeing inside the patient

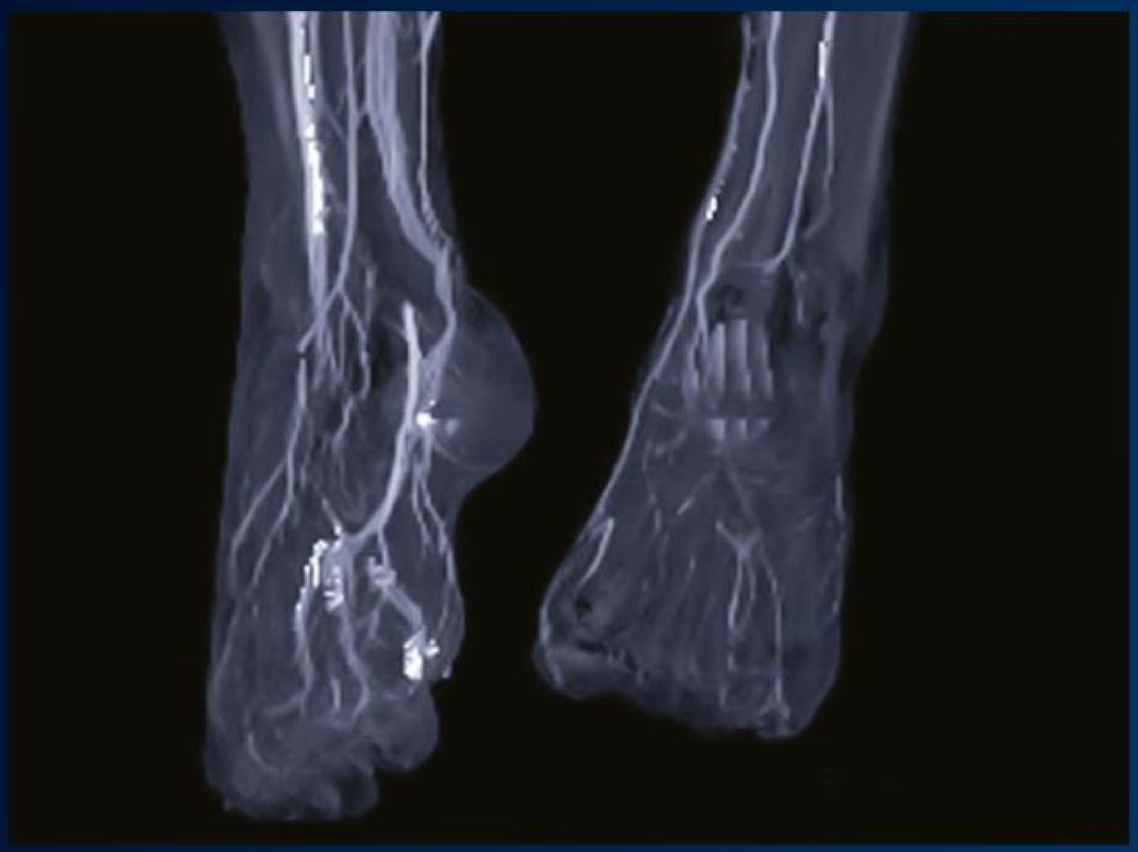
All surgeries benefit from making as accurate and small incisions as possible, but in some instances – such as spinal surgery – this accuracy becomes imperative. A pioneering new surgical technology called OpenSight couples digital models based on patient scans with augmented reality HoloLens technology to paste a patient's internal structures over their skin in real time. The digital model moves with the surgeon, providing both 2D images and 3D projections of the internal organs and tissues. This helps the surgical team to assess the patient, pre-plan the procedure in detail and make precise incisions when the operation begins.



OpenSight and HoloLens technology gives surgeons a detailed view of the patient's interior

Preparing for AR surgery

Step by step, how medical practitioners are able to see through our skin during an operation



1 Scanning the body The patient first undergoes a CT scan that captures the positions of their bones, blood vessels, connective tissues, muscles and fat.

2 Converting the scan An algorithm pores through the scan data and creates a set of polygonal models and digital images that the surgeon's HoloLens can use.

3 Mapping the model The generated data is mapped onto the patient, enabling the surgeon to see a digital version of the patient's interior during surgery.

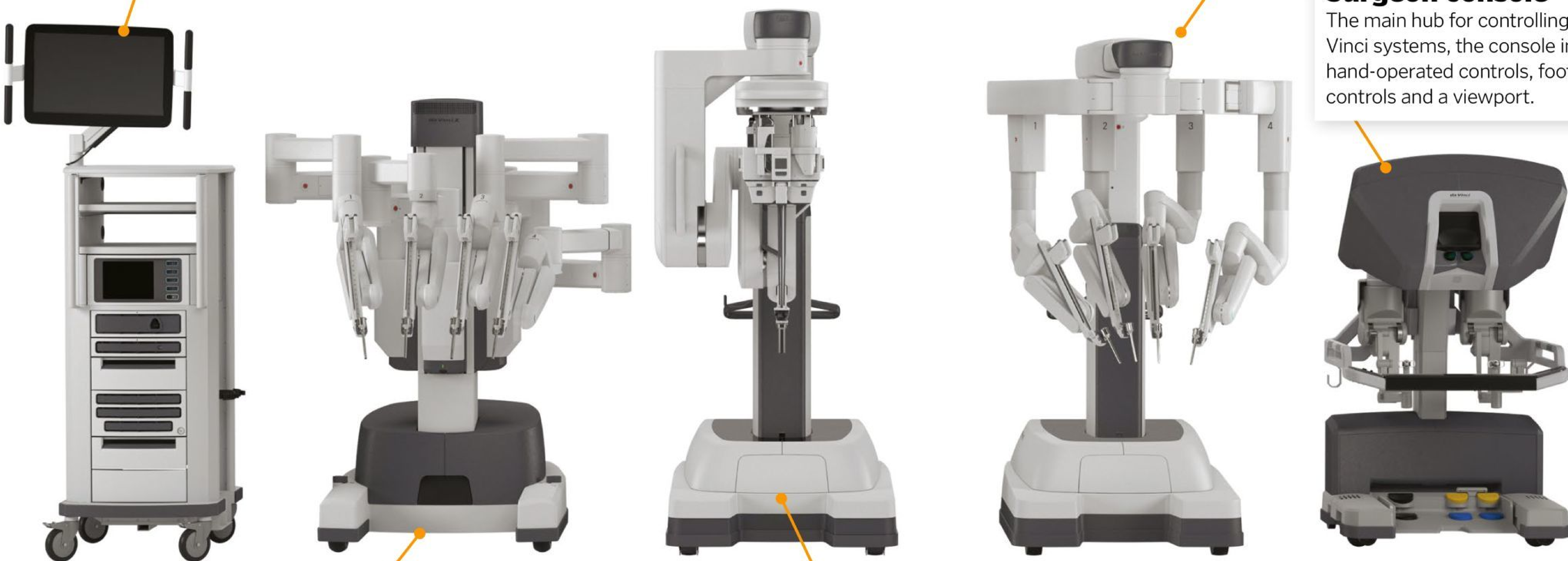
The da Vinci devices

Uncover the array of surgical systems available to today's top surgeons

Vision cart
Used by other members of the surgical team to keep up to date on progress via live-streaming video footage.

The da Vinci SP
A single robotic arm hosting a 3D-HD camera and three multi-jointed instruments can be used for single-point-of-entry procedures.

Surgeon console
The main hub for controlling the da Vinci systems, the console includes hand-operated controls, foot pedal controls and a viewport.



The da Vinci X
The little brother to the Xi, this system is equipped with modular components and can be upgraded to suit the needs of the operating theatre.

The da Vinci Xi
Equipped to handle a slew of complex procedures, the Xi has advanced hardware and software and can even reposition the operating table during surgery.

technology, grants the surgeon super-human vision. Additionally, the interconnectivity between surgical teams around the world means that expertise can be shared more equally between hospitals in poorer and wealthier areas.

There are some procedures, however, where even augmented reality-equipped surgeons will be surpassed by those using robotics to enhance their precision in the operating theatre. Established robotic systems, such as the da Vinci Surgical System explored in this feature, are capable of conducting minimally invasive procedures that are largely unmatched by human hands. With improved dexterity, a multitude of arms and internal 3D views, robotics unlocks new possibilities in surgeries that were previously inhibited by a surgeon's limited view and restricted range of motion.

As with all technologies, surgical robotics is being increasingly miniaturised to help with implementation in an array of operating theatres and to tackle even more precise procedures. One concept that meets these aims is the Axsis design, a machine that uses flexible arms with pincers on their ends to tackle eye cataract

Miniature, flexible robotic systems are being developed to treat the sensitive surface of the eye

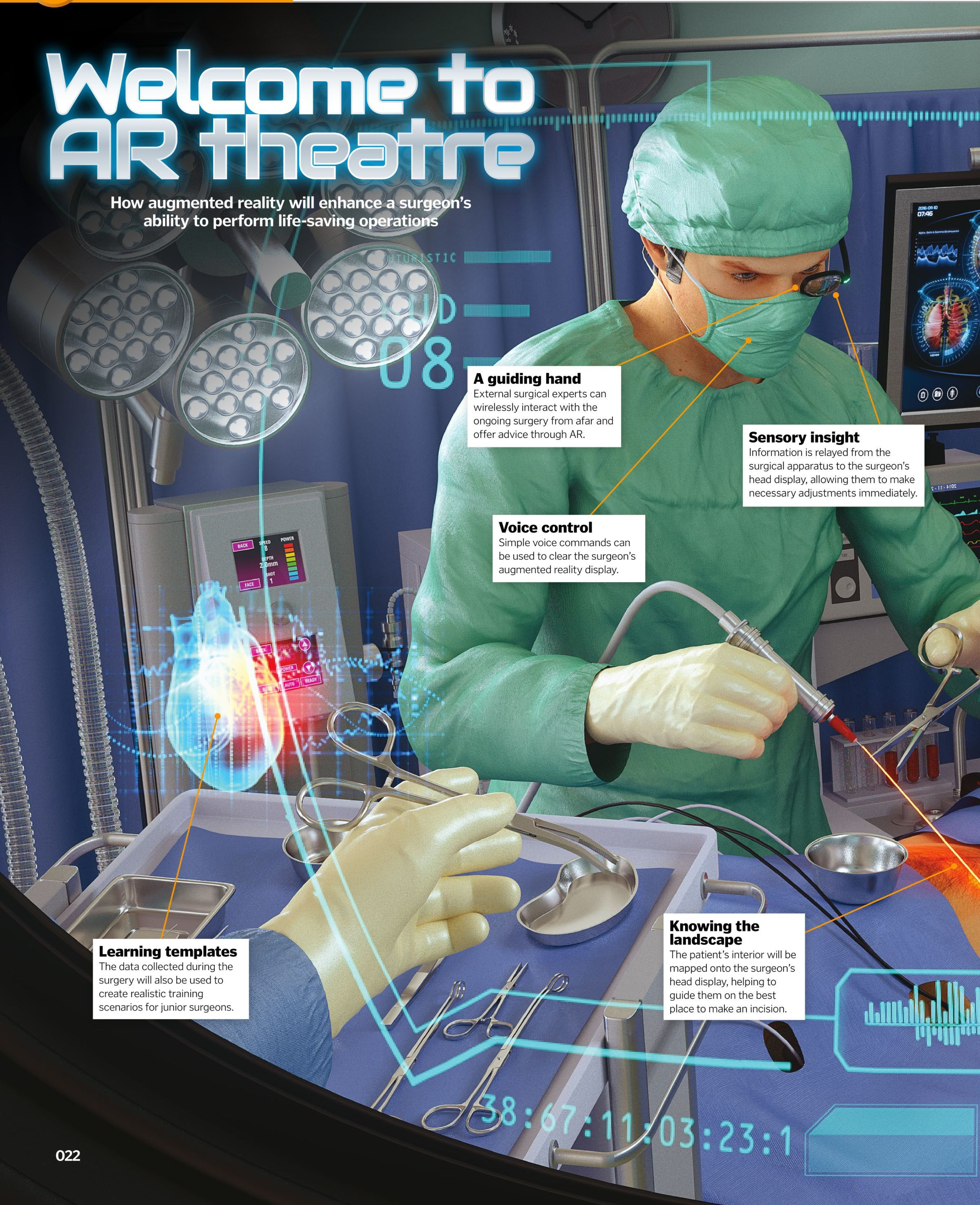
AR technology is useful for both planning and performing surgery

4 Refining details
A mesh-processing step boosts the accuracy of the digital model, meaning the surgeon can be confident about the interior tissue's position.

5 AR surgery
The surgeon wears a HoloLens during surgery, showing them the locations of tissues and structures.

Welcome to AR theatre

How augmented reality will enhance a surgeon's ability to perform life-saving operations



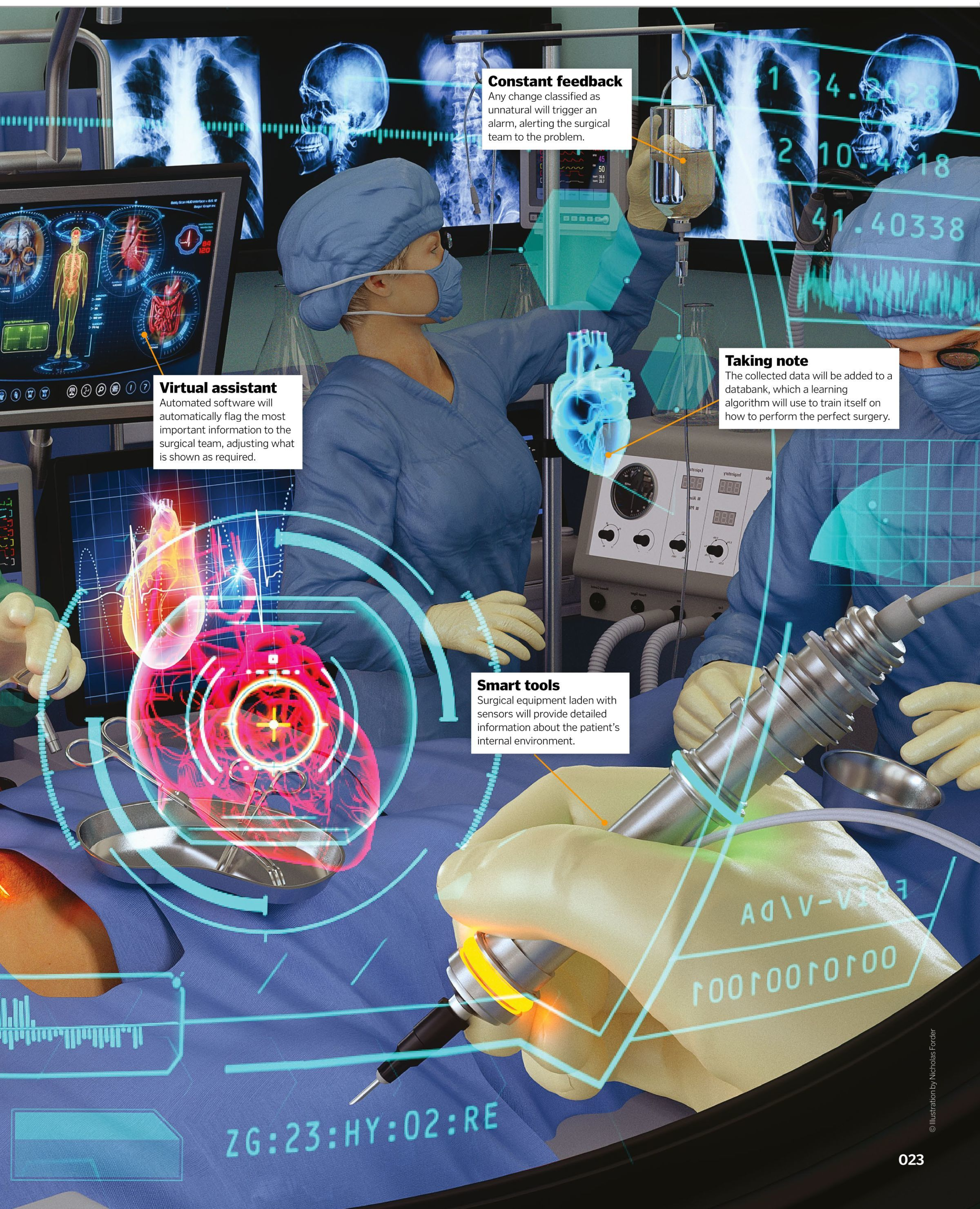
A guiding hand
External surgical experts can wirelessly interact with the ongoing surgery from afar and offer advice through AR.

Sensory insight
Information is relayed from the surgical apparatus to the surgeon's head display, allowing them to make necessary adjustments immediately.

Voice control
Simple voice commands can be used to clear the surgeon's augmented reality display.

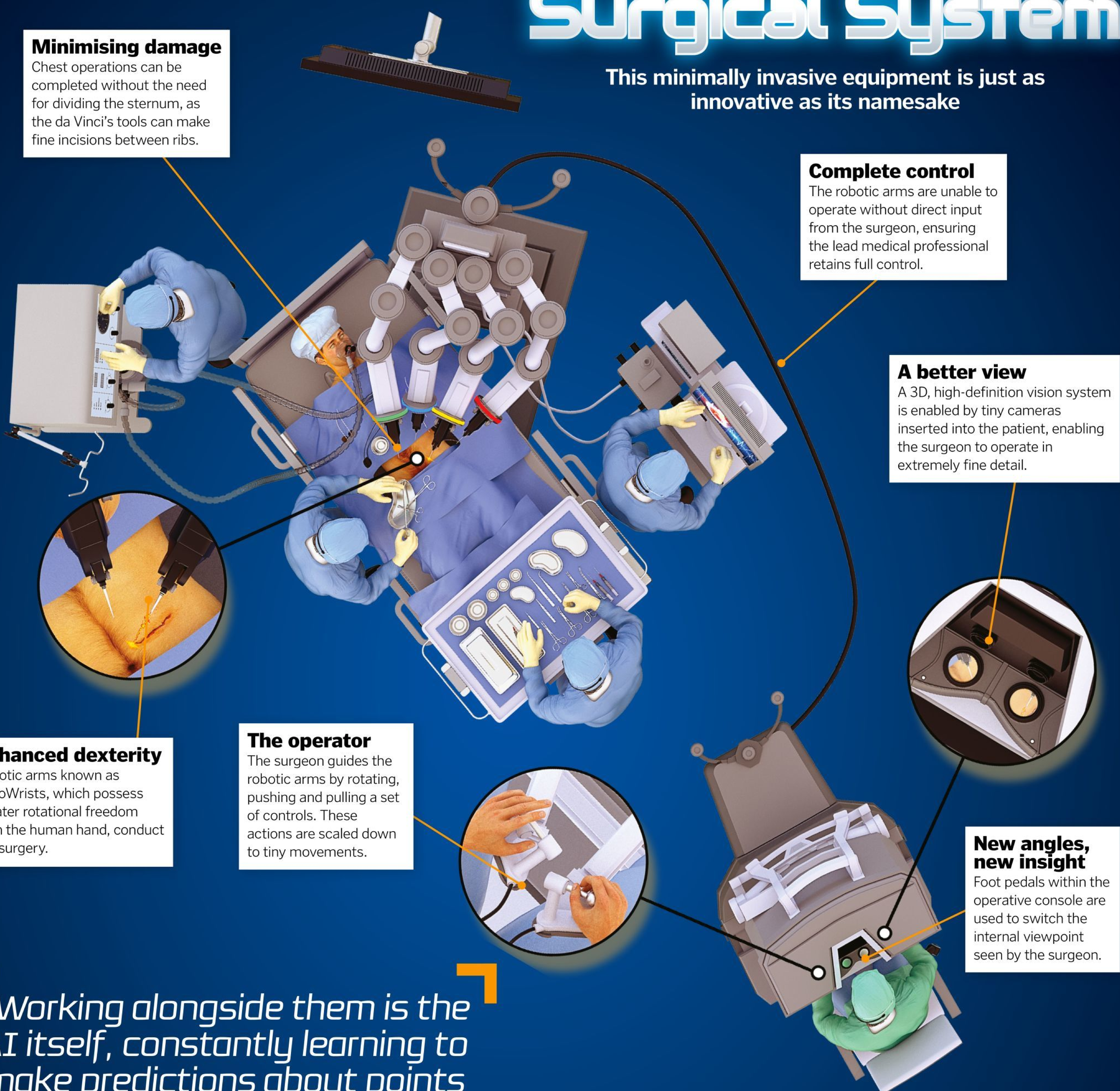
Learning templates
The data collected during the surgery will also be used to create realistic training scenarios for junior surgeons.

Knowing the landscape
The patient's interior will be mapped onto the surgeon's head display, helping to guide them on the best place to make an incision.


Constant feedback
Any change classified as unnatural will trigger an alarm, alerting the surgical team to the problem.
Virtual assistant
Automated software will automatically flag the most important information to the surgical team, adjusting what is shown as required.
Taking note
The collected data will be added to a databank, which a learning algorithm will use to train itself on how to perform the perfect surgery.
Smart tools
Surgical equipment laden with sensors will provide detailed information about the patient's internal environment.

The da Vinci Surgical System

This minimally invasive equipment is just as innovative as its namesake



> *"Working alongside them is the AI itself, constantly learning to make predictions about points of stress in the system"*

$6.4 billion
The estimated value of the surgical robotics market by 2020

4,500+
The number of da Vinci robots worldwide of which over 70 are used in UK hospitals

750,000
The amount of remote clinical encounters facilitated by telehealth network InTouch Health

PARO, an interactive robot modelled on a seal, was designed to comfort patients in recovery

400kg
The weight of medication carried by the nursing assistant TUG robot

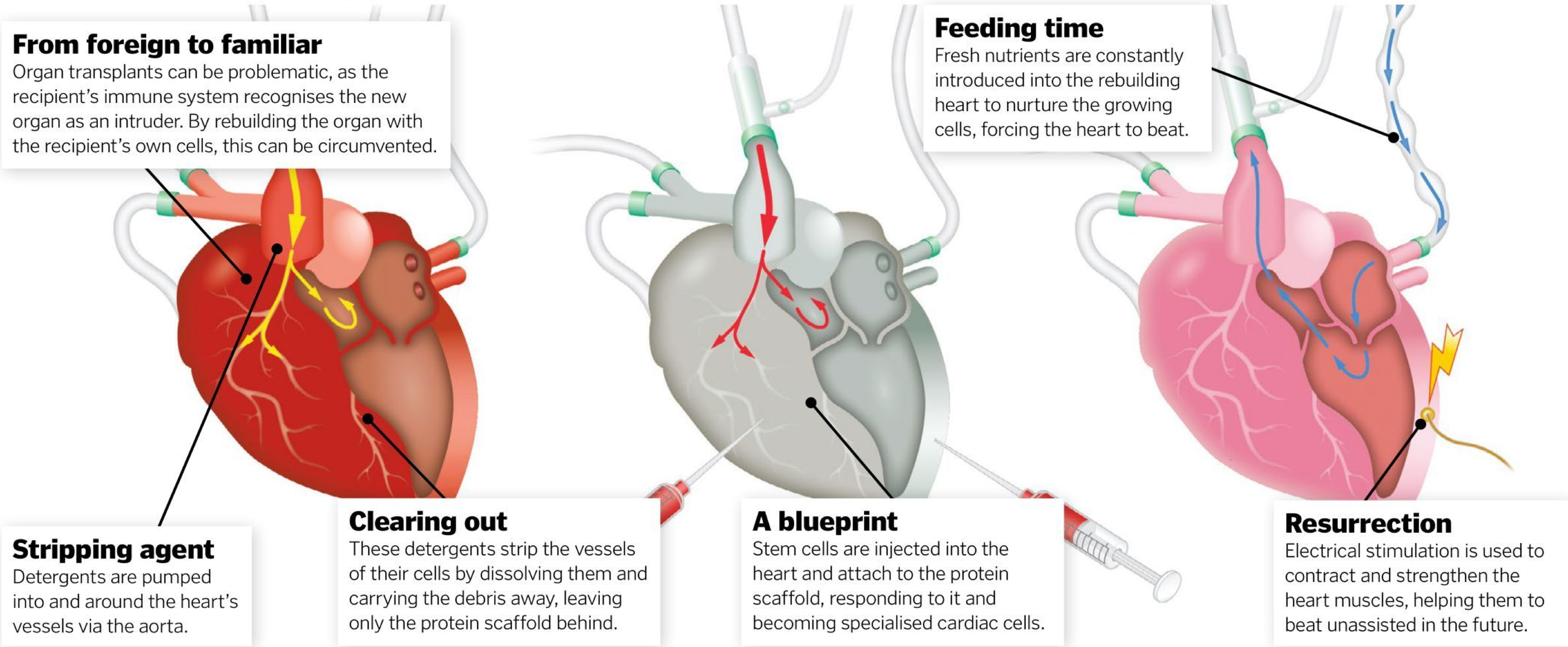
40
The number of times the Robear nursing robot can lift patients each day

The iKnife surgical tool heats tissue to diagnose cancer

Microrobots that can migrate through blood vessels are currently being developed by the Max Planck Society

Retrofitted organs

How surgeons convert donor hearts into replacements suitable for any patient, through bioengineering



surgery. The accuracy of the 1.8mm arms are reinforced by image-guidance software and an artificial intelligence that will advise and inform the medical practitioner during surgery.

The miniature technologies may not stop there. NASA has partnered with medical company Virtual Incision to create a small robot that can be operated remotely by a surgeon for small operations in low gravity. If it's a success, we may find these robots in use on Earth too.

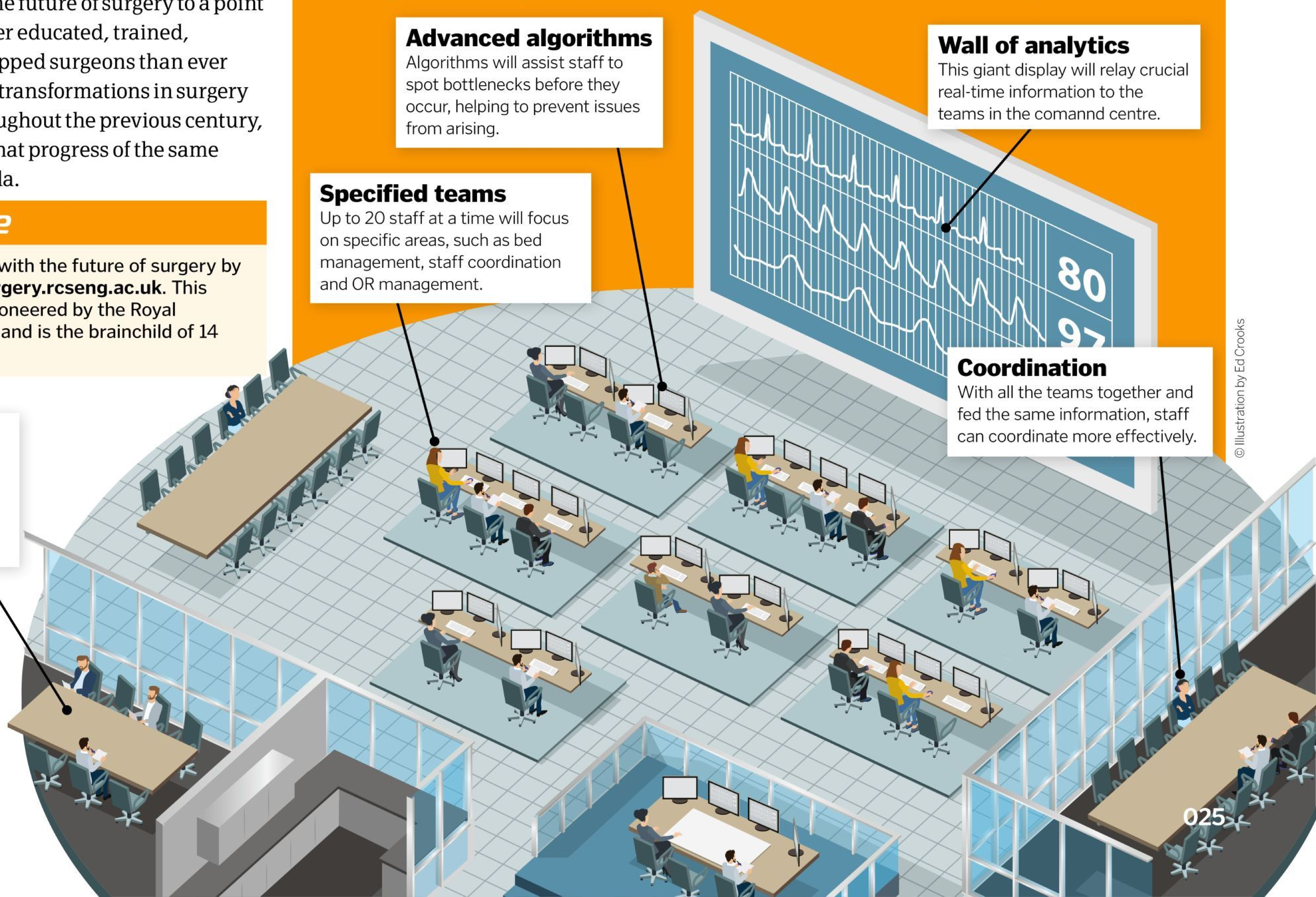
Tools such as Axsis, da Vinci, HoloLens and others are driving the future of surgery to a point where we have better educated, trained, connected and equipped surgeons than ever before. And like the transformations in surgery that happened throughout the previous century, we can be hopeful that progress of the same scale is on the agenda.

Learn more

Continue to engage with the future of surgery by visiting: **futureofsurgery.rcseng.ac.uk**. This visionary site was pioneered by the Royal College of Surgeons and is the brainchild of 14 surgical experts.

Surgery command centre

We live in an era of big data. In all fields, especially medicine, we are collecting swathes of data aimed at improving patient care. But when handled improperly, this can impair the level of care rather than improve it. To ensure they make the best use of patient data and learn from it, GE Healthcare and the Bradford Royal Infirmary have teamed up to create an AI command centre. Equipped with a wall of analytics showing the most important information, allocated sections for coordinators and a central platform for the supervisor to overview the situation, the command centre seems like it would fit in better at NASA than a hospital. But with this hub of data, the coordination teams can allocate care where it's needed most. Working alongside them is the AI itself, constantly learning from the stream of data to make predictions about stress points in the system, advising the team to act before the problem arises.



The World Health Organization recommends that everyone has ten routine immunisations

How vaccines save lives

These injections, drops and sprays train your immune system to fight deadly diseases

Made up of millions of individual white blood cells, the immune system patrols the body in search of germs. When tissues are under threat, it mounts a two-pronged attack. First, the innate immune system gets to work to slow germ growth and prevent spread. Then the adaptive immune system comes in to eliminate the threat.

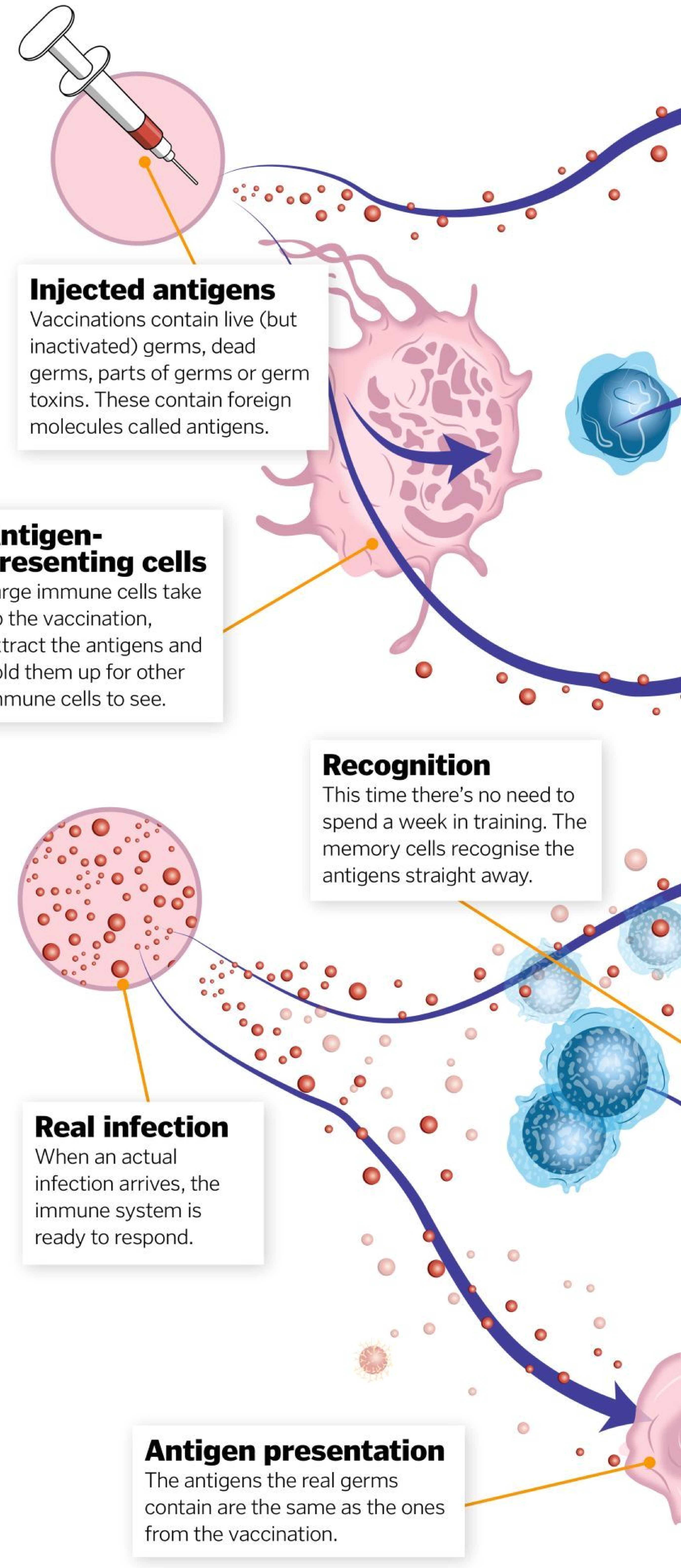
The adaptive immune system has powerful weaponry, but it takes a while to deploy. This is because the cells of the adaptive immune system can each only attack one type of infection. When the body encounters a new germ, it needs to find the right cells and prepare them for battle. This process can take up to one week, and in that time people can sometimes become very unwell.

This is where vaccines come in. Rather than wait to encounter a dangerous disease like measles in the world, a vaccine gives the immune system a chance to prepare in advance. Vaccines contain weakened or dead germs, or parts of germs, along with something called an adjuvant. This helps to alert the immune system to danger, encouraging it to start mounting an attack. With access to parts of the germ, the immune system can find the right cells and get them ready.

Many of the cells made during a vaccination disappear afterwards, but some stick around as 'memory cells'. They stay in the bloodstream for decades, constantly on the lookout for their matching germ. If the infection then happens for real, these memory cells spring into action straight away. They divide to produce an army of clones that appears in a matter of hours instead of days. This can clear the infection before it takes hold, preventing us from getting sick at all.

What happens when you're vaccinated?

Vaccinations prepare the immune system to fight infections with speed and precision

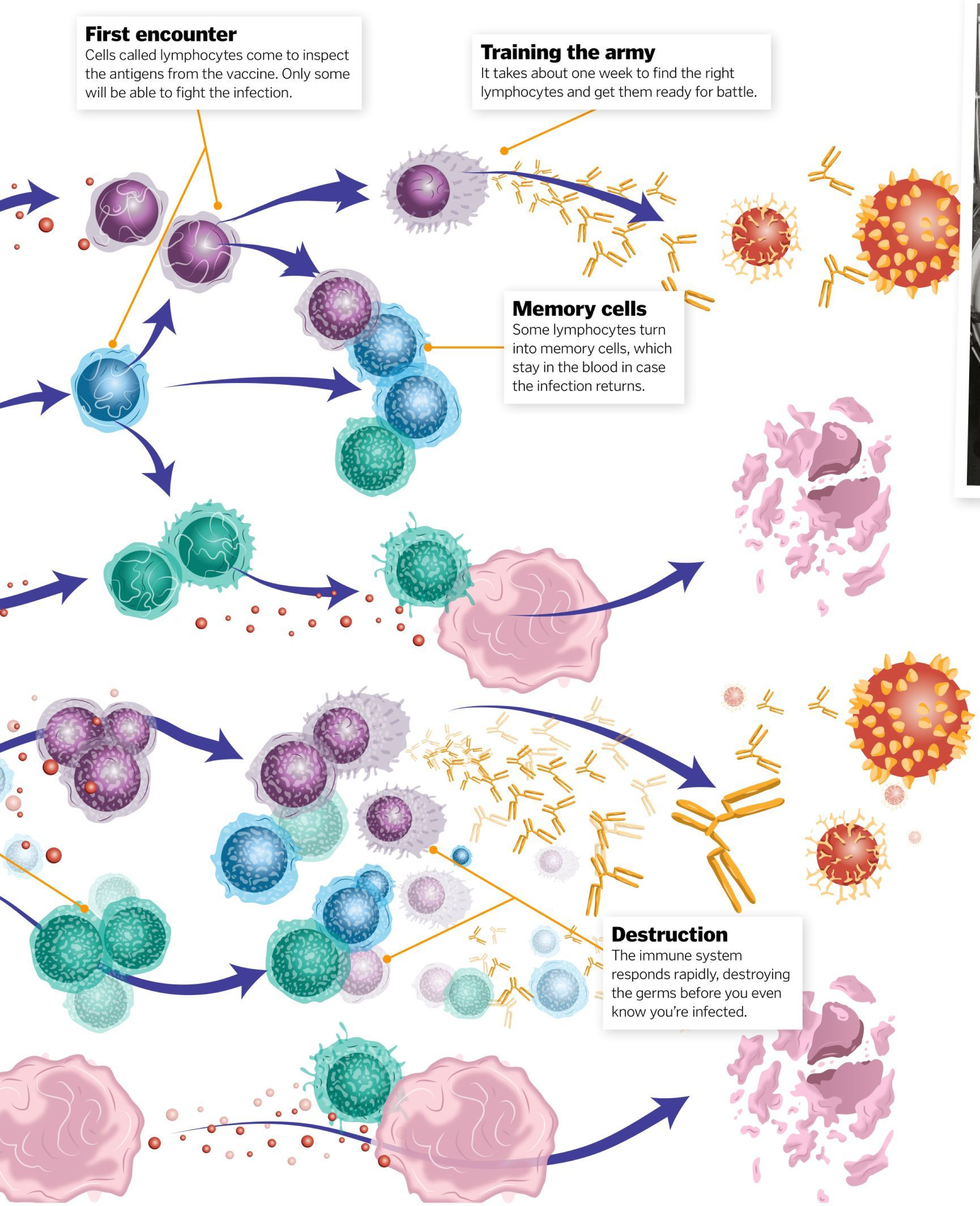


Falling vaccination rates are causing measles outbreaks in the US and Europe

Are vaccines dangerous?

Without our current vaccinations, 2.5 million children would die every year. If we used the same vaccinations to immunise more children, we could save 1.5 million more lives. But in some countries vaccination rates are dropping. To stop the spread of measles, 95 per cent of children need to have had their MMR vaccine, but in England in 2017–18 uptake was only 91.2 per cent. At this level herd immunity stops working and the virus can start to spread.

There are some concerning vaccine myths, but the truth is that vaccinations save lives. Babies are able to cope with millions of germ cells every day; vaccinations won't overload or weaken their immune systems, even if they were born prematurely. It's safe to vaccinate children if they have a mild illness or allergies. There is absolutely no link to autism. And if you or your children haven't had vaccinations, it's never too late to go and get them done.



Before vaccinations, iron lungs helped children to breathe when polio paralysed their muscles

5 FACTS ABOUT HOW VACCINES SAVE LIVES

1 Smallpox
Smallpox used to kill 5 million people every year. Now it kills none. Thanks to a worldwide vaccination campaign the disease disappeared in 1980 – the only infectious disease to have been eradicated.

2 Diphtheria
The skin and respiratory infection diphtheria would kill 260,000 people every year if it weren't for vaccination. Immunisation prevents at least 86 per cent of infections worldwide.

3 Whooping cough
Without vaccination, there would be nearly 1 million deaths from whooping cough every year. Immunising young babies has reduced that number by two-thirds.

4 Measles
Measles can cause blindness, brain swelling and severe lung problems. It takes just two doses of the vaccine to protect children from infection, preventing 2.6 million deaths every year.

5 Neonatal tetanus
Newborn babies are especially vulnerable to tetanus infection. Thanks to vaccination, 700,000 more babies are now surviving every single year.

Next-gen vaccines

The science of immunisation is only just beginning. The Human Vaccines Project is bringing the world's top scientists together to unlock the secrets of immune response. To design the vaccines of the future we need to understand our own immune defences. The Human Immunome Program is mapping the genes that allow the immune system to make custom antibodies for different germs. The Rules of Immunity Program is discovering what rules the immune system uses to build a defence and remember past infection. The more we know about how our immune system army works, the better we'll get at training it to fight disease.

Flu viruses change every year, so we have to change our vaccines to keep up

How we taste

Explore the body's fifth sense and how our tongues translate chemical information to our brains

Taste is produced by the body's biological translation of flavour. The responsibility of detecting taste, however, doesn't fall solely on the tongue, as it works in tandem with the nose.

Before any food has reached the mouth, olfactory (smell) receptors are triggered by volatile odorants (smell compounds) entering the nasal canal. A series of electrical impulses, called action potentials, are created along the adjoining nerve cells, which inform the olfactory cortex of the brain about the scent's identity.

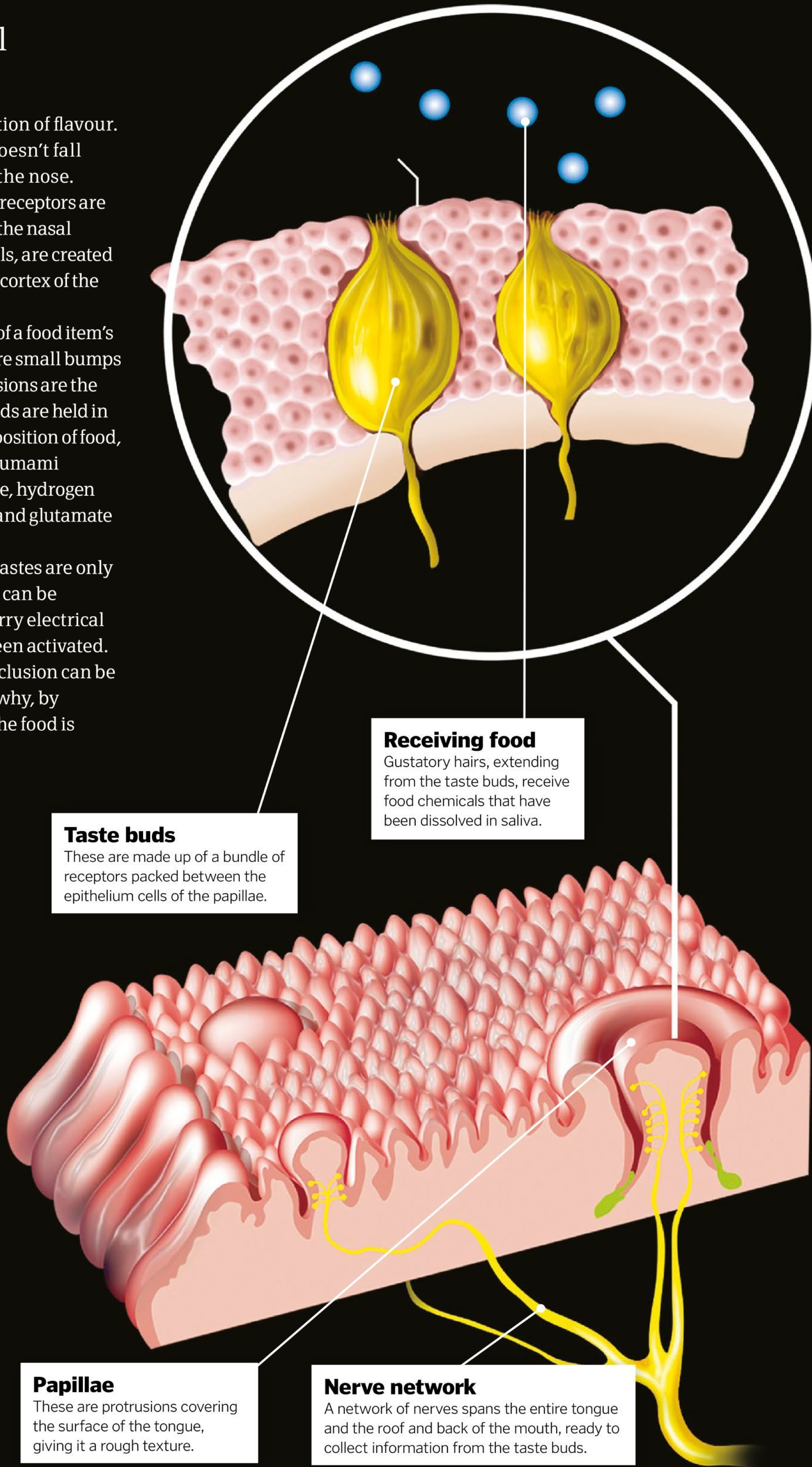
This is when the tongue's role completes the decryption of a food item's taste. Spread across the length and breadth of the tongue are small bumps called papillae. Often mistaken as taste buds, these protrusions are the gateways to taste perception. Around 50-100 taste pores/buds are held in the cellular walls of a papilla and detect the chemical composition of food, dividing it into five categories: sweet, bitter, salty, sour and umami (savoury). Foods high in sodium chloride trigger a salty taste, hydrogen triggers sour, sucrose leads to sweet, quinine brings bitter and glutamate (a savoury food compound) results in umami.

However, it is a common misconception that these five tastes are only detected in certain regions of the tongue. In fact, each one can be detected all over. Once a chemical is detected, neurons carry electrical impulses to the brain, informing it of which flavour has been activated.

Together with the information obtained by smell, a conclusion can be drawn about what you're eating and how it tastes. This is why, by pinching your nose while you eat, the brain can detect if the food is sweet or sour but not its distinct flavour.

From fork to frontal lobe

Discover the chemical journey that triggers our ability to enjoy food



Receiving food
Gustatory hairs, extending from the taste buds, receive food chemicals that have been dissolved in saliva.

Taste buds
These are made up of a bundle of receptors packed between the epithelium cells of the papillae.

Papillae
These are protrusions covering the surface of the tongue, giving it a rough texture.

Nerve network
A network of nerves spans the entire tongue and the roof and back of the mouth, ready to collect information from the taste buds.

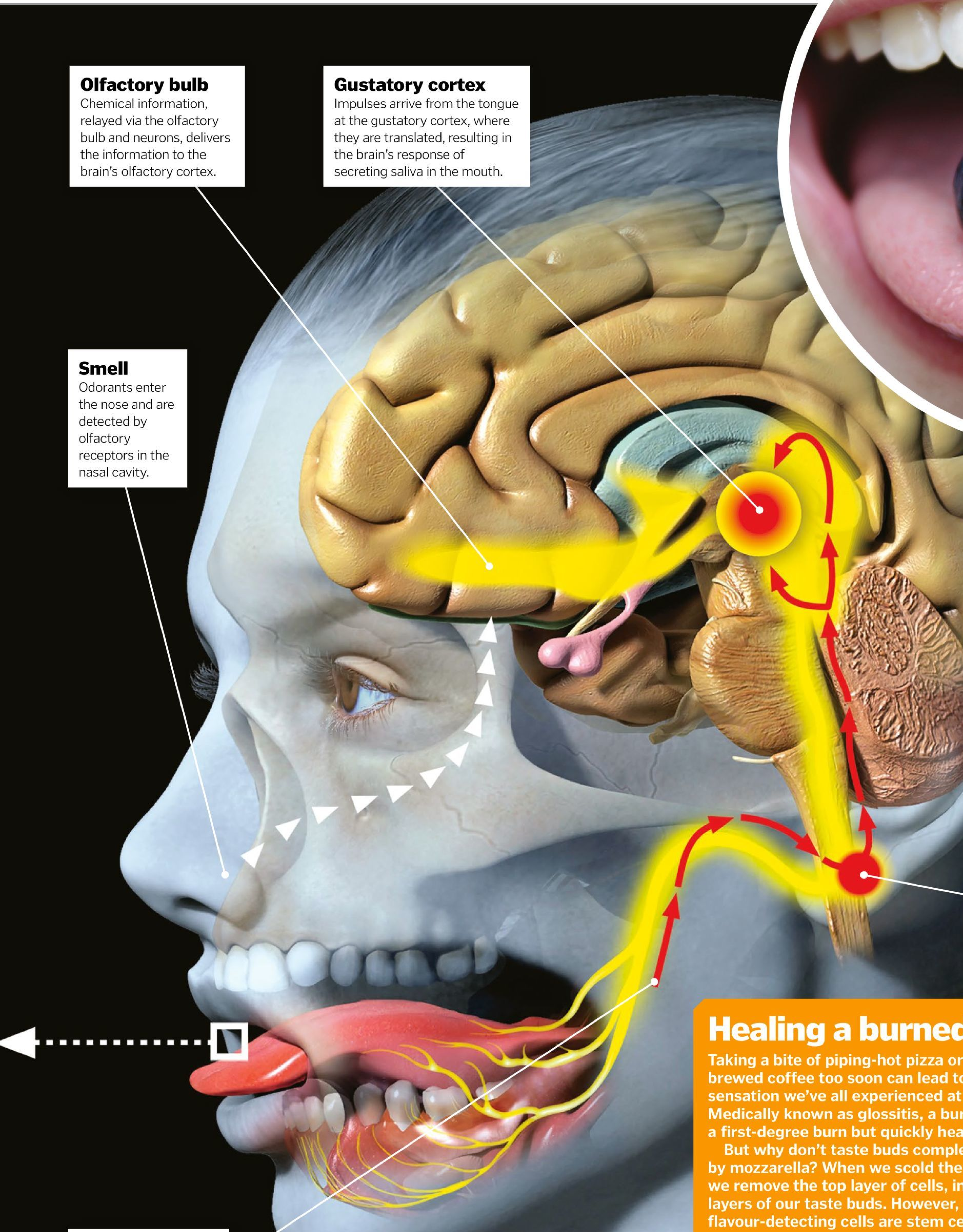
The science of spice

Feeling the initial burn of a jalapeño pepper, you might expect spice to be classed as one of the core categories of flavour, alongside sweet and sour. However, the tongue's perception and the body's reaction to spicy food is a result of a chemical crossover. For the purpose of preventing the body ingesting hot (temperature) food, vanilloid/capsaicin receptors on the tongue alert the brain when extreme heat is present in the mouth. Eating chilli peppers has the same effect on the body thanks to their chemical composition.

Varying in degrees of concentration along the Scoville scale, capsaicinoids are a chemical compound found in spicy food and activate the capsaicin receptors. Just like when you eat hot food, the body's response to spice is to perspire to cool down, release endorphins and increase blood circulation. So rather than being classed as a flavour, spice is merely a chilli's ability to masquerade as heat.

The world's hottest chilli is the Carolina Reaper – it's 200-times hotter than a jalapeño pepper

Thousands of tiny taste buds on our tongues act as culinary detectives for flavour



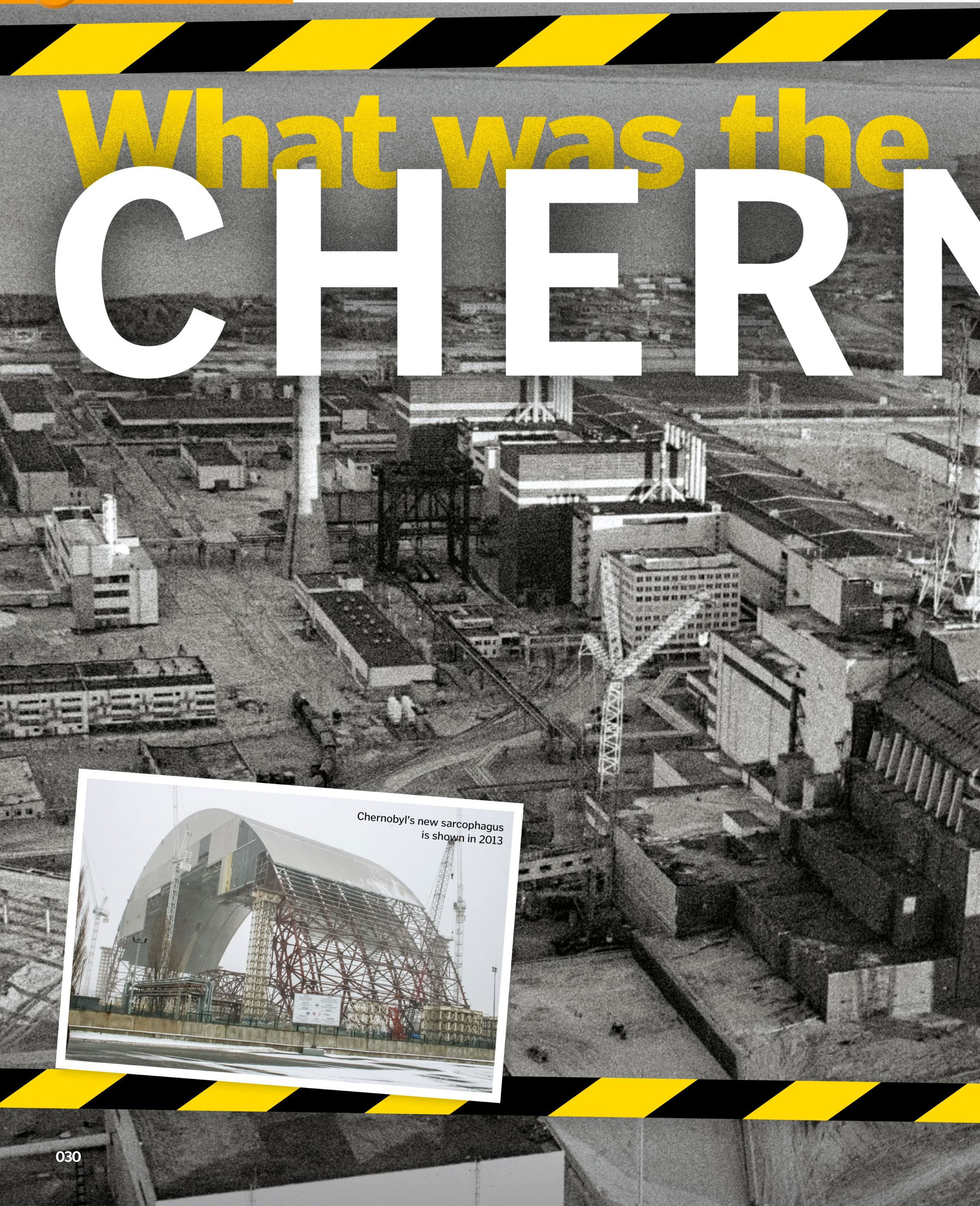
Healing a burned tongue

Taking a bite of piping-hot pizza or sipping a freshly brewed coffee too soon can lead to that scorching sensation we've all experienced at one time or another. Medically known as glossitis, a burnt tongue is classed as a first-degree burn but quickly heals in a day or two.

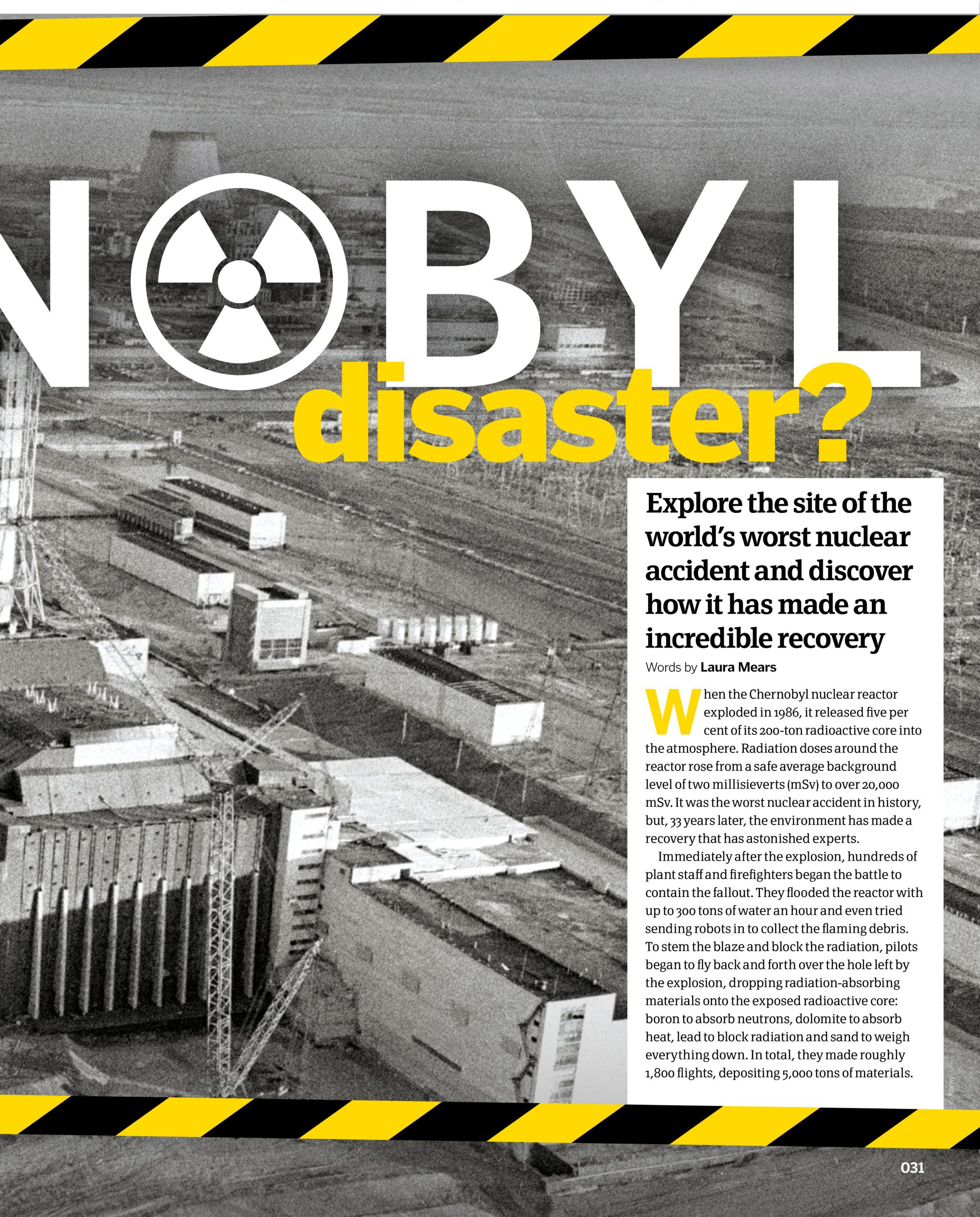
But why don't taste buds completely die when melted by mozzarella? When we scold the surface of our tongues we remove the top layer of cells, including the upper layers of our taste buds. However, within the bundle of flavour-detecting cells are stem cells known as basal cells. Typically replacing the gustatory receptor cells every ten days or so, these regenerative cells morph into replacement receptors quickly, restoring your taste – that is until you take another bite of pizza.

Our taste buds are kept fresh by regenerative stem cells

What was the CHERN



Chernobyl's new sarcophagus is shown in 2013



NOBYL disaster?

Explore the site of the world's worst nuclear accident and discover how it has made an incredible recovery

Words by **Laura Mears**

When the Chernobyl nuclear reactor exploded in 1986, it released five per cent of its 200-ton radioactive core into the atmosphere. Radiation doses around the reactor rose from a safe average background level of two millisieverts (mSv) to over 20,000 mSv. It was the worst nuclear accident in history, but, 33 years later, the environment has made a recovery that has astonished experts.

Immediately after the explosion, hundreds of plant staff and firefighters began the battle to contain the fallout. They flooded the reactor with up to 300 tons of water an hour and even tried sending robots in to collect the flaming debris. To stem the blaze and block the radiation, pilots began to fly back and forth over the hole left by the explosion, dropping radiation-absorbing materials onto the exposed radioactive core: boron to absorb neutrons, dolomite to absorb heat, lead to block radiation and sand to weigh everything down. In total, they made roughly 1,800 flights, depositing 5,000 tons of materials.


Trees have flourished in the town of Pripyat in the years since the disaster

As they worked, dust and debris from the explosion climbed a kilometre into the air, and wind blew the fallout – radioactive dust and particles from the reactor that literally fell out of the sky – to the northwest. The most dangerous particles were caesium and iodine, both of which get into the food chain and can cause damage to DNA. The caesium-137 particles were large, so they didn't travel far. They collided with trees and buildings close to the power plant and coated the ground when it rained. They settled on skin and clothes, entered rivers and streams and seeped through the soil into the groundwater. This contamination covered an area spanning 200,000 square kilometres around the site.

The iodine-131 particles were smaller, allowing them to travel further. They rose high into the sky, scattering across Europe, with some traces reaching as far as the US and Japan.

The most immediate danger was to the people in the surrounding area. Those within 4,300 square kilometres were at risk of a potentially deadly lifetime radiation exposure of more than 350 mSv. Some of the 45,000 residents of the nearest town, Pripyat, had already received 50 mSv of radiation. So they, and more than 150,000 others in the surrounding area, had to evacuate. To this day, a 30-kilometre exclusion zone remains in force around the reactor, and it has been deemed too dangerous for humans to return to for at least 20,000 years.

As residents moved out, hundreds of thousands of workers moved in. These 'liquidators' washed radioactive dust from the streets with a thick liquid they called molasses. They bulldozed dead trees, buried broken equipment and knocked down contaminated buildings. They received radiation doses of between 100 and 500 mSv, putting their own health at risk. Of those that responded first, 237 became ill with acute radiation sickness. But, thanks to their work, radiation levels in the exclusion zone started to drop.

As time has passed, radioactive decay has made the exclusion zone even safer. Iodine-131 has a half-life of just eight days, and caesium-137 a half-life of 30 years. As the years go by, the danger from radiation is steadily falling.


The exclusion zone is home to hundreds of stray dogs, descended from abandoned pets

When the accident happened, the worst of the fallout hit the trees. They absorbed between 60 and 90 per cent of the radioactive cloud, experiencing radiation levels of 5 mSv an hour. As a result, 400 hectares of pine forest turned red and died, taking bees, butterflies and spiders with it. As rain washed the particles into the clay soil and new trees started to grow, the radioactive particles began to cycle through the ecosystem. They got into mushrooms on the forest floor, lichens on branches and from there into grazing animals like elk and deer. But, as the years since the disaster have passed, the forest has started to recover.

Birch and aspen trees have grown up in place of the damaged pines. They still take in radiation from the soil, but animals have started to return. Mouse and vole numbers have returned to normal, and larger animals are taking advantage of the empty spaces left by humans.

What caused the meltdown?

The night of the disaster, shift supervisor Aleksandr Akimov received orders to test reactor 4 at the Chernobyl Nuclear Power Plant. The plant worked by pumping water past hot nuclear fuel, creating steam, which drove two turbines. His superiors wanted to know what would happen if the main electricity cut out, so they disabled some of the automatic safety features to conduct a test. Worried that it was a bad idea, Akimov resisted, but eventually he agreed to shut the system down for 20 seconds. However, the control rods that should have slowed the nuclear reactions actually caused the power to surge. The water in the reactor boiled, the pressure rose and the 1,000-ton reactor top broke free. This jammed the control rods, and the tubes containing the nuclear fuel started to crack. Then the reactor exploded.


Helicopters dropped sand on the reactor in an attempt to contain the radiation

Timeline of Chernobyl

26 APRIL 1986
Reactor 4 at the Chernobyl Nuclear Power Plant explodes, and firefighters battle to put out the blaze.

27 APRIL 1986
Helicopters make hundreds of trips over the reactor, dropping sand, lead and boron to absorb the radiation.

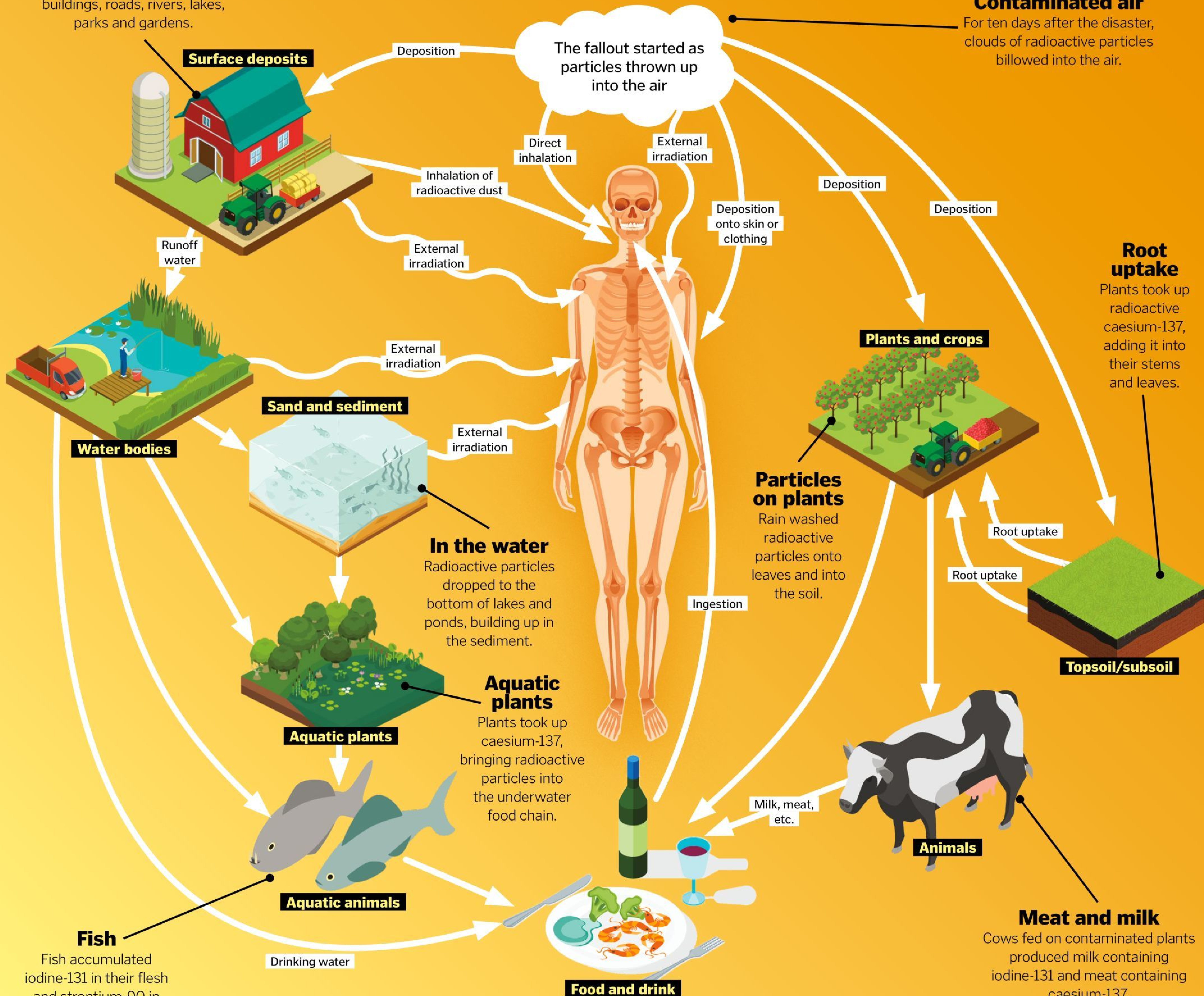
10 MAY 1986
Roughly two weeks later, the fire inside reactor 4 is finally extinguished.

NOVEMBER 1986
Liquidators complete construction of a concrete sarcophagus, covering the remains of the reactor.

1987–1991
Hundreds of thousands of liquidators work inside the exclusion zone to wash, bulldoze and bury contaminated buildings and trees.

HOW THE RADIATION SPREAD

Nuclear fallout moved through the environment in the days, weeks and months after the disaster



Surface dust
Radioactive particles coated buildings, roads, rivers, lakes, parks and gardens.

Contaminated air
For ten days after the disaster, clouds of radioactive particles billowed into the air.

Root uptake
Plants took up radioactive caesium-137, adding it into their stems and leaves.

Particles on plants
Rain washed radioactive particles onto leaves and into the soil.

In the water
Radioactive particles dropped to the bottom of lakes and ponds, building up in the sediment.

Aquatic plants
Plants took up caesium-137, bringing radioactive particles into the underwater food chain.

Fish
Fish accumulated iodine-131 in their flesh and strontium-90 in their bones.

Meat and milk
Cows fed on contaminated plants produced milk containing iodine-131 and meat containing caesium-137.

1991
Chernobyl's three other nuclear reactors are still running. A fire in reactor 2 convinces authorities to shut it down.

2011
Radiation levels have dropped. Ukraine's Emergencies Ministry starts allowing tourists to visit.

2015
Census data reveals that elk, roe deer, red deer and wild boar are thriving inside the zone.

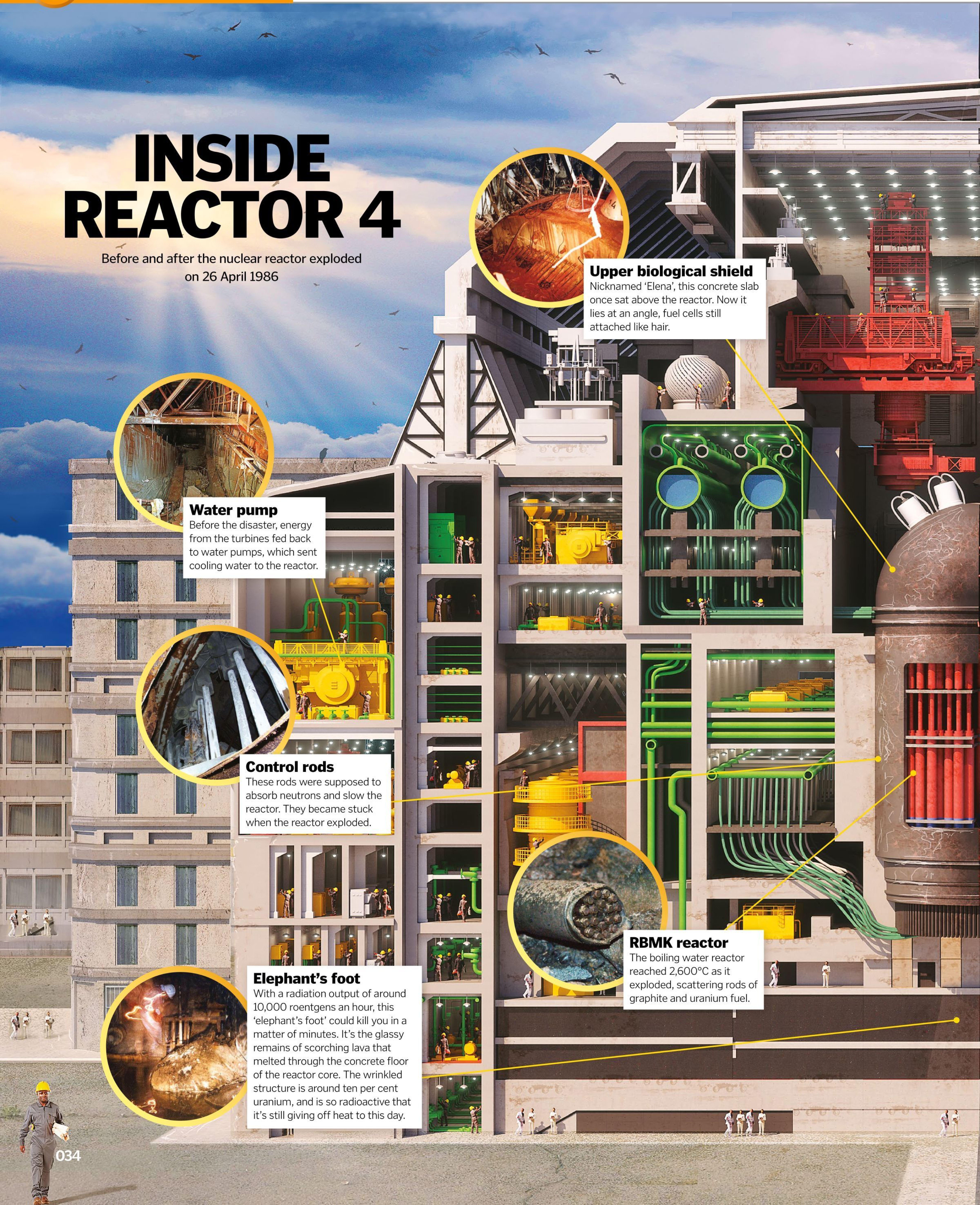
2016
The New Safe Confinement shelter slides into place over the old sarcophagus.

2018
The Chernobyl Power Plant gets a new lease of life with 4,000 new solar modules.

2019
Radiation levels just outside the New Safe Confinement now barely rival a dental X-ray.

INSIDE REACTOR 4

Before and after the nuclear reactor exploded on 26 April 1986



Upper biological shield

Nicknamed 'Elena', this concrete slab once sat above the reactor. Now it lies at an angle, fuel cells still attached like hair.

Water pump

Before the disaster, energy from the turbines fed back to water pumps, which sent cooling water to the reactor.

Control rods

These rods were supposed to absorb neutrons and slow the reactor. They became stuck when the reactor exploded.

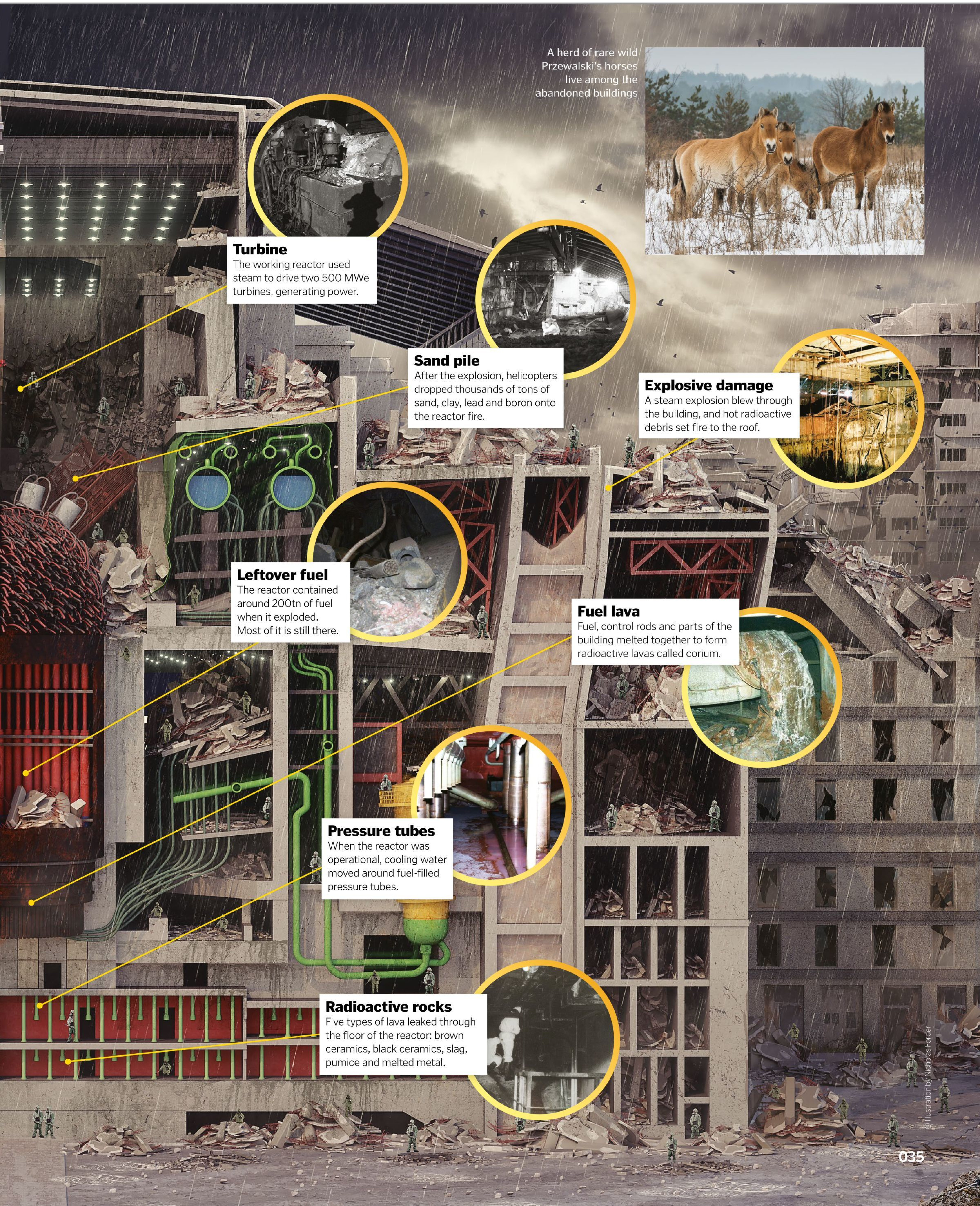
RBMK reactor

The boiling water reactor reached 2,600°C as it exploded, scattering rods of graphite and uranium fuel.

Elephant's foot

With a radiation output of around 10,000 roentgens an hour, this 'elephant's foot' could kill you in a matter of minutes. It's the glassy remains of scorching lava that melted through the concrete floor of the reactor core. The wrinkled structure is around ten per cent uranium, and is so radioactive that it's still giving off heat to this day.

A herd of rare wild Przewalski's horses live among the abandoned buildings



Enter the forest today and you'll find wild boar, brown bears, elk, roe deer, wolves, lynx and bison. Incredibly, numbers of endangered birds like black storks and white-tailed eagles are higher inside the exclusion zone than anywhere else in Ukraine.

Some areas of the forest are still hot with radiation. Here, animal tracks disappear and birds go quiet. In these regions there are no organisms to break down falling leaves, so the litter on the forest floor is much thicker than it should be. To reduce the risk of fire, a herd of rare Przewalski's horses have been introduced into the zone to graze the forest floor. And, despite the radiation, they seem to be thriving.

With plants and animals flourishing across the exclusion zone, scientists have been working on ways to make the ground safe to farm again. Plants grown on contaminated soil take in caesium particles and aren't yet safe for humans to eat. But researchers have discovered that potassium fertilisers can stop plants taking up radioactive particles. Straw around the base of the plants can then stop radiation getting back into the soil. Even simply ploughing the Earth can help to reduce hot spots by spreading out the radioactive particles. While each method only makes a small difference, combining them together could make the ground safe once again.

As the exclusion zone recovers, one major problem still remains. Reactor 4 is still there, along with 95 per cent of its radioactive fuel, and the cement sarcophagus built around it in the 1980s is crumbling. If it starts to collapse, it could release fresh clouds of radioactive dust into the air.

To stop this from happening, an international team completed a New Safe Confinement shelter in 2016 to contain the dust in case of collapse. Cranes will painstakingly disassemble the rubble so that the high-level waste can be removed and buried safely. Beneath the shield, radiation levels still reach up to 500 mSv per hour. But outside, life is returning to normal. Standing directly on the new arch is now no more dangerous than having a dental X-ray. Thanks to intensive work over the past 30 years, the Chernobyl exclusion zone is starting to recover.

1,000 'self-settlers' returned to the zone to live on the radioactive land

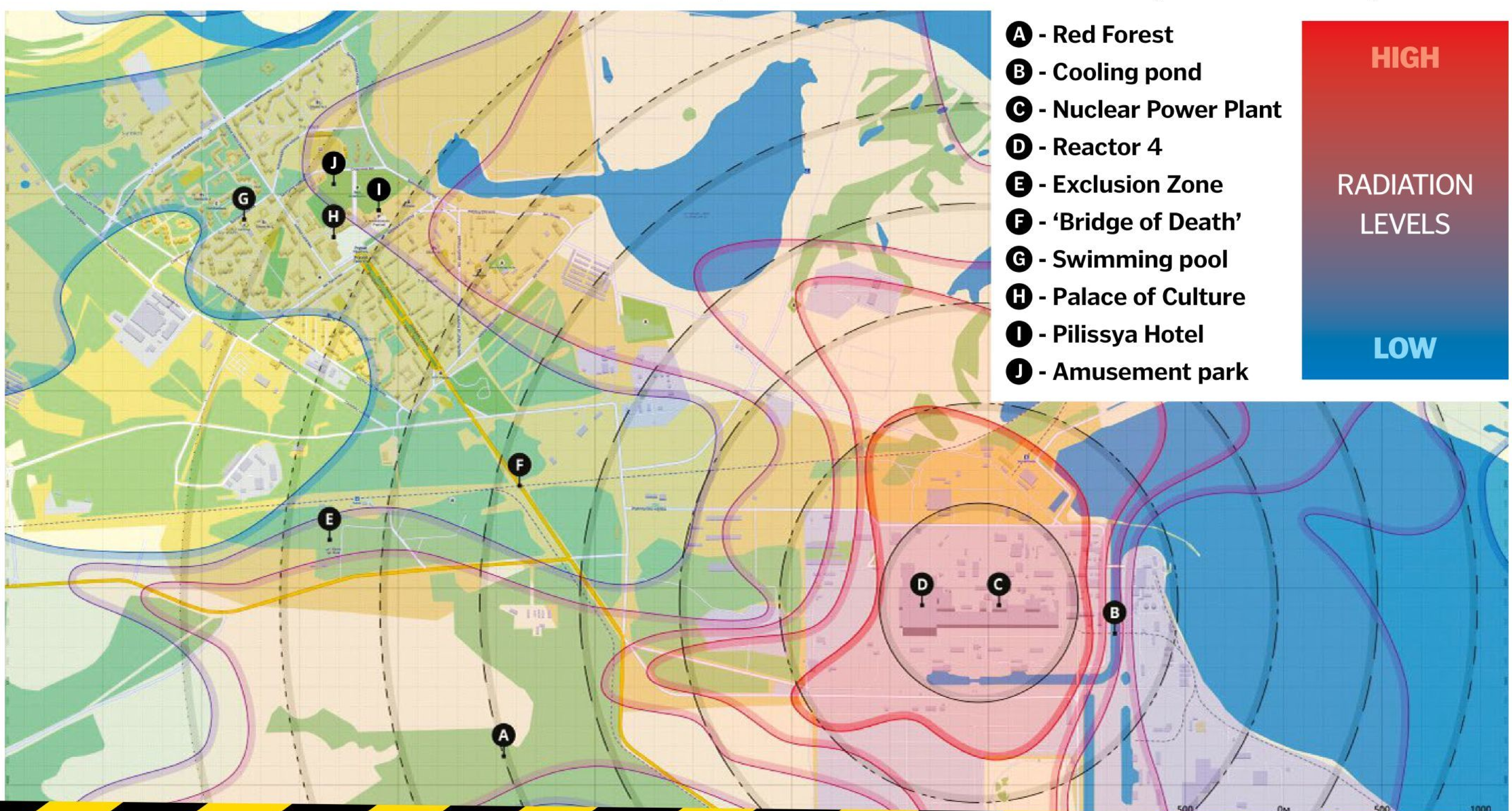
Wolves faced extinction in Europe, but they're thriving inside the exclusion zone

Why Chernobyl's wolves thrive

Forests still have some of the highest contamination of any ecosystem inside the exclusion zone. But that hasn't deterred the local wildlife. Some of Europe's most elusive mammals have made their homes between the trees, and they seem to be thriving. It appears European grey wolves would rather face low-level radiation than risk living alongside humans. There are now seven times more wolves inside the zone than in protected areas nearby. Without us to interfere, they are free to chase deer, catch fish and even eat fruit from abandoned orchard trees. In fact, conditions are so good that scientists have spotted young males leaving the exclusion zone in search of more room.

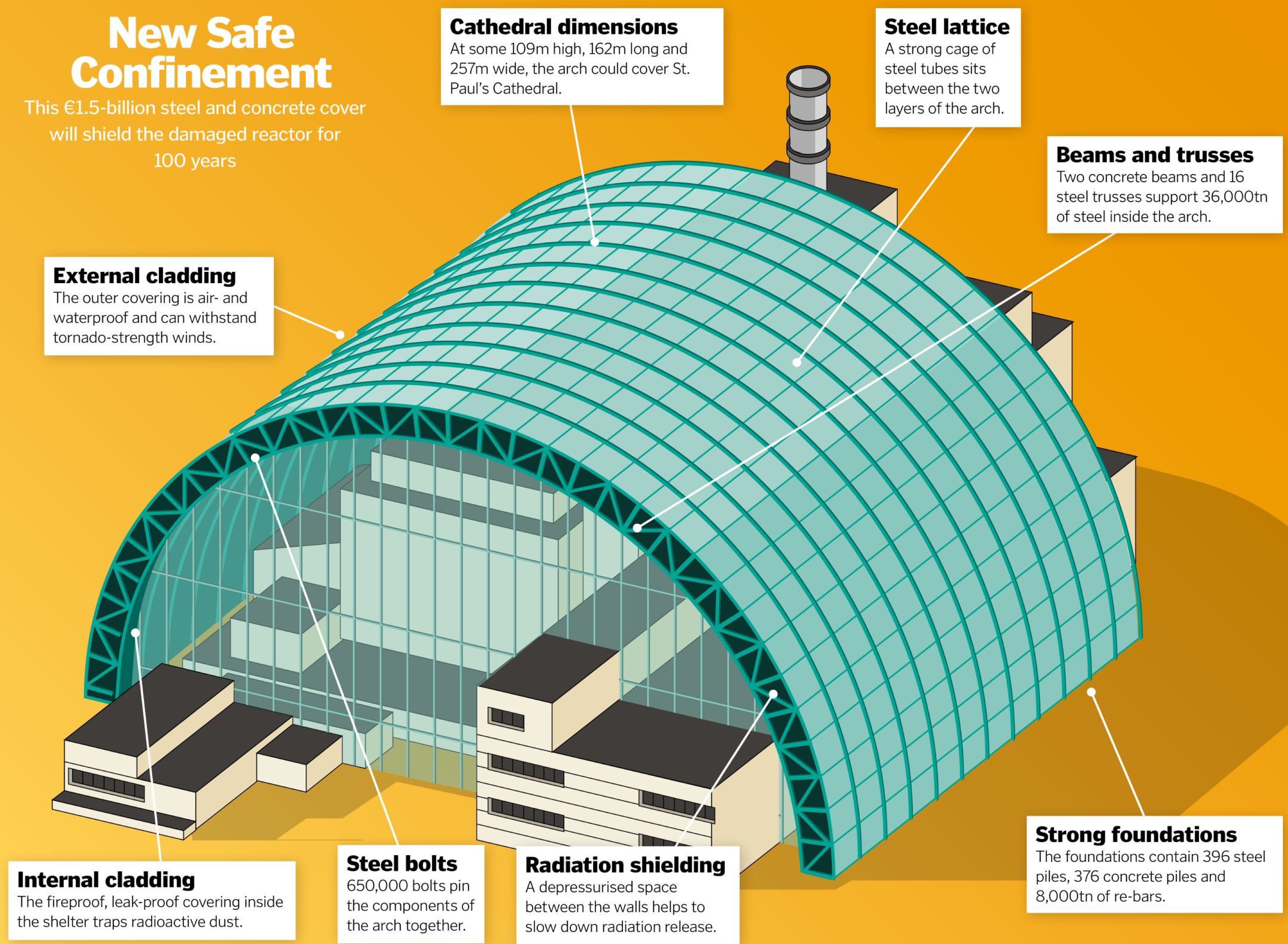
Exclusion zone radiation

This heat map reveals radiation levels inside the Chernobyl exclusion zone today



New Safe Confinement

This €1.5-billion steel and concrete cover will shield the damaged reactor for 100 years



WHAT REMAINS?

The disaster has had a lasting effect on the surrounding area

2,000 tons of combustible materials like graphite and bitumen

4 tons of radioactive dust and particles

630,000 cubic metres of contaminated radioactive waste

1,300 tons of hardened radioactive lava

200 tons of unspent uranium fuel

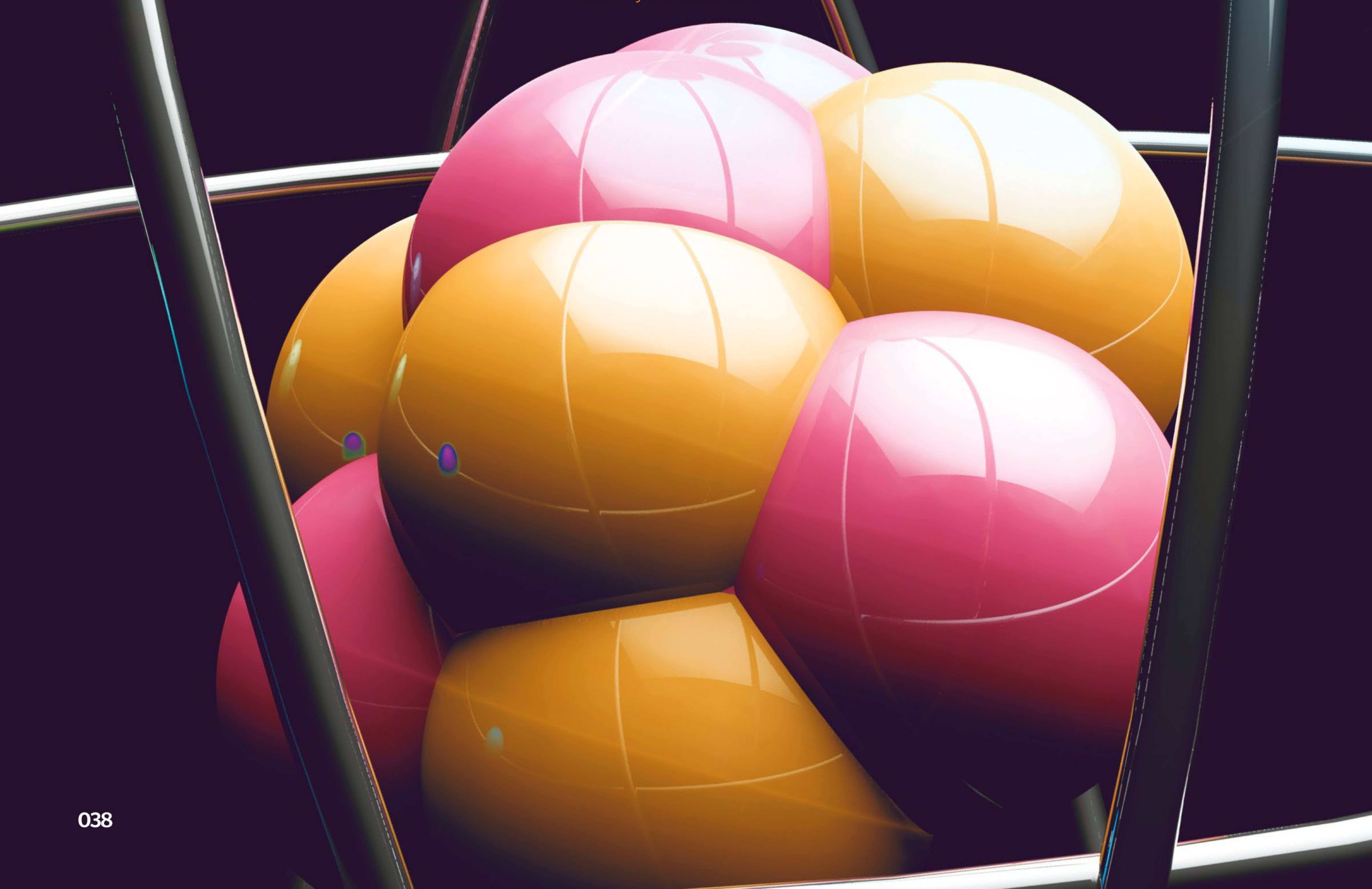
43,000 cubic metres of high-level waste containing spent nuclear fuel

1,500 roentgens of radiation released every hour under the reactor

ATOM ANATOMY

The structure of these microscopic building blocks drives the chemistry of the universe

Words by **Laura Mears**



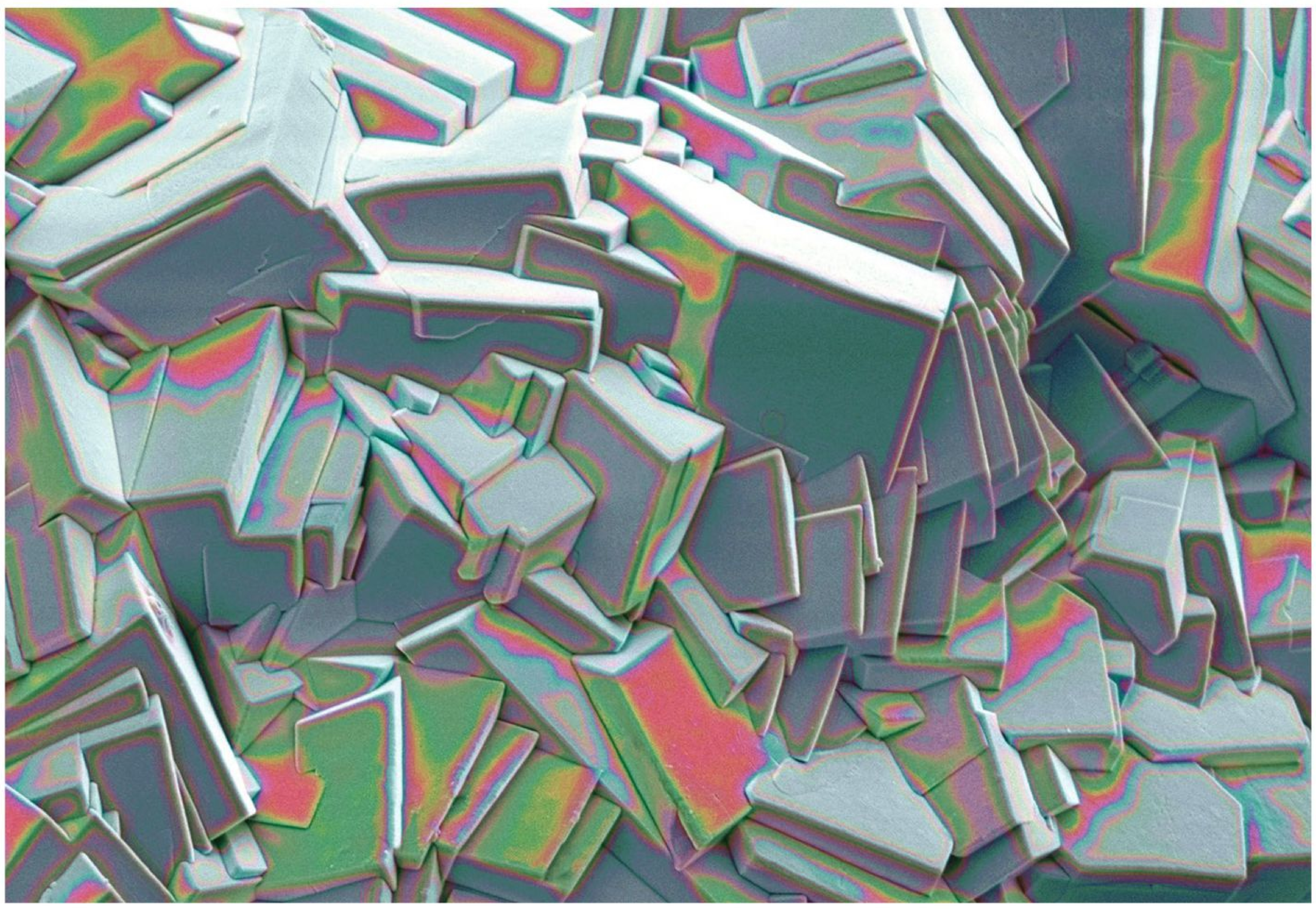
Atoms are the building blocks of everything around you, from the cells in your body to the cup of tea in your hand. Made from elementary particles and held together by fundamental forces, they drive the chemistry of the universe.

Each one has a tiny, positively charged nucleus, balanced by a cloud of negatively charged electrons. These determine the atom's properties. Split an atomic nucleus open and you'll find subatomic particles called protons and neutrons. The simplest atom, hydrogen, has just one proton and no neutrons. But as you move up through the periodic table the number of protons rises one by one. With each extra proton, the behaviour of the atom changes.

Protons have a positive charge, so for every extra one added the atom also gains another negative electron. These electrons cluster in fixed zones around the atomic nucleus, known as orbitals or shells. Each shell can only hold a certain number of electrons. So when a shell fills up, the next electrons have to start a new one.

Atoms are most stable when their electron shells are full, but most elements have electrons to spare. This is the driving force behind the chemistry we see around us. To complete half-filled shells, atoms form chemical bonds. They can either share their electrons to form

"Split an atomic nucleus open and you'll find subatomic particles"

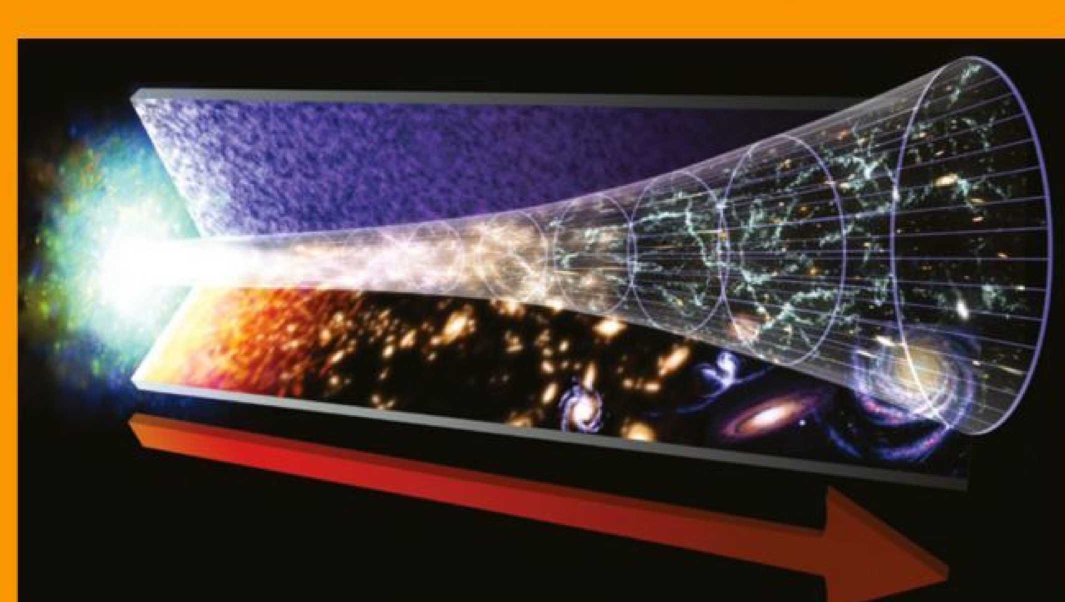


These are sugar crystals magnified 1,250 times by a scanning electron microscope

The birth of atoms

13.8 billion years ago the Big Bang created the universe. In the first moments it was so hot and dense that no particles could survive. Whenever quarks and electrons burst into existence, they immediately broke apart. But as the universe expanded and started to cool, these elementary particles became more stable. Then quarks started to come together to form protons and neutrons. Within minutes, these were combining to form the first atomic nuclei.

It took another 380,000 years for the universe to cool enough to allow complete hydrogen atoms to form, and then the real magic started to happen. Gravity started to pull the atoms into clumps, and as those clumps grew the pressure inside started to build. The atomic nuclei got so close together that they started to fuse, and the first stars burst into life. These vast nuclear furnaces have been fusing atomic nuclei ever since, creating all the different elements we see around us today.



Hydrogen atoms were the first to form after the birth of the universe

Different elements can combine together to make complicated compounds

What your tea's made of

There are more atoms in a cup of tea than cups of water in all the oceans

MIXTURE

Your cup of tea is a mixture; a combination of different molecules and compounds not linked by chemical bonds. It contains water, as well as the molecules from the tea itself: polyphenols, amino acids, enzymes, pigments, volatiles and caffeine. Perhaps milk is there too, which contains fats, proteins and sugars. And maybe also table sugar.

Scale: **10 centimetres**

COMPOUND

If you stuck a powerful microscope into your tea, you'd start to see the compounds that make up the mixture. Compounds are substances made from two or more different elements bonded together. Caffeine has the chemical formula $C_8H_{10}N_4O_2$. It contains eight carbon atoms, ten hydrogen, four nitrogen and two oxygen.

Scale: **0.78 nanometres**

MOLECULE

Break caffeine into pieces and you'd end up with molecules. These contain just one type of atom and are the smallest units that can take part in chemical reactions. If you broke the caffeine compound up, its oxygen atoms would pair together, forming an oxygen molecule with two identical atoms.

Scale: **292 picometres**

ELEMENT

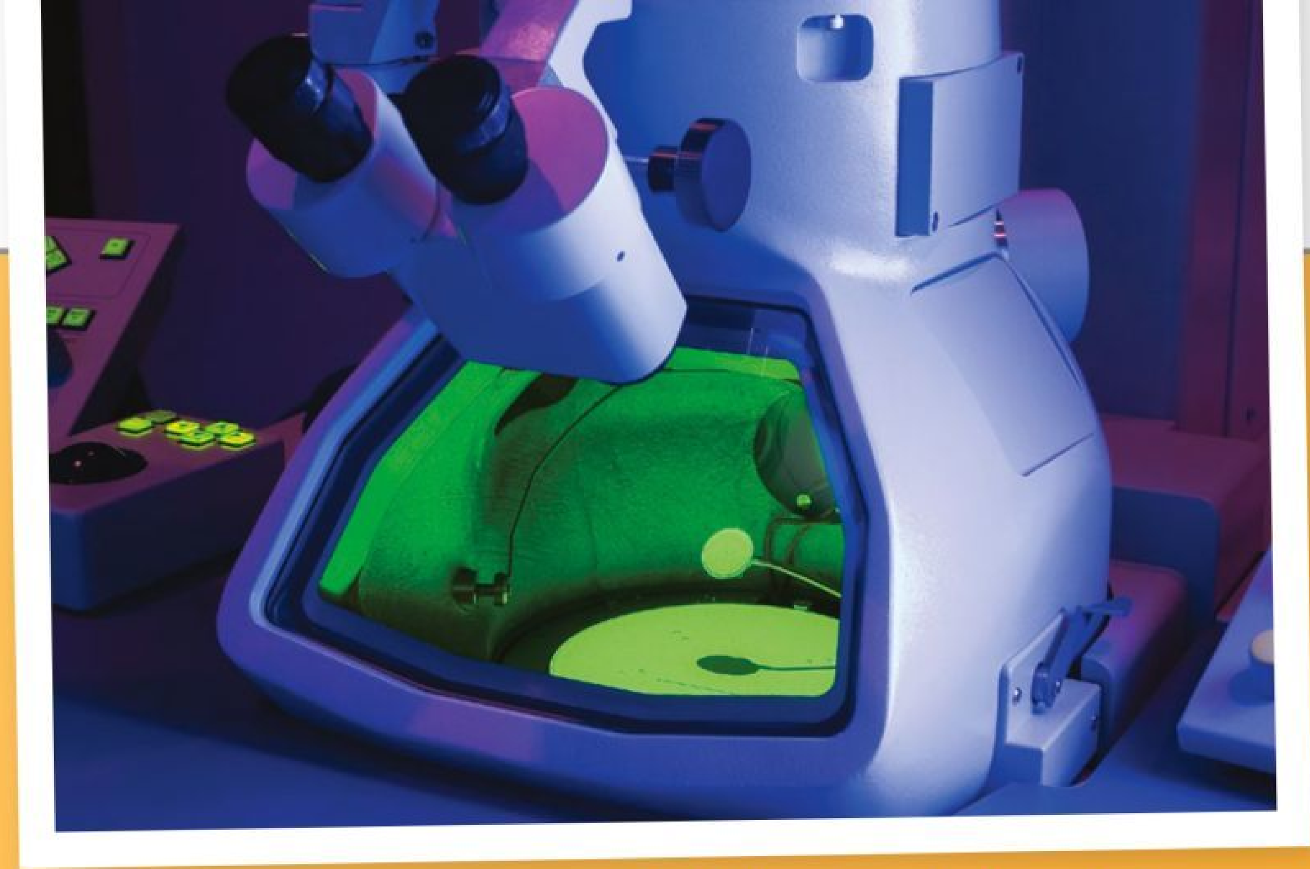
Zoom in on an oxygen molecule and you'd see the individual oxygen element. Elements are substances that contain only one type of atom. There are over 90 naturally occurring elements on Earth, and even more made synthetically in laboratories. Oxygen is element number 8.

Scale: **60 picometres**

ATOM

One final zoom would reveal the subatomic particles inside the atoms: positive protons, neutral neutrons and negative electrons. The numbers of each give different elements their distinctive chemical properties. An oxygen atom contains eight protons, eight neutrons and eight electrons.

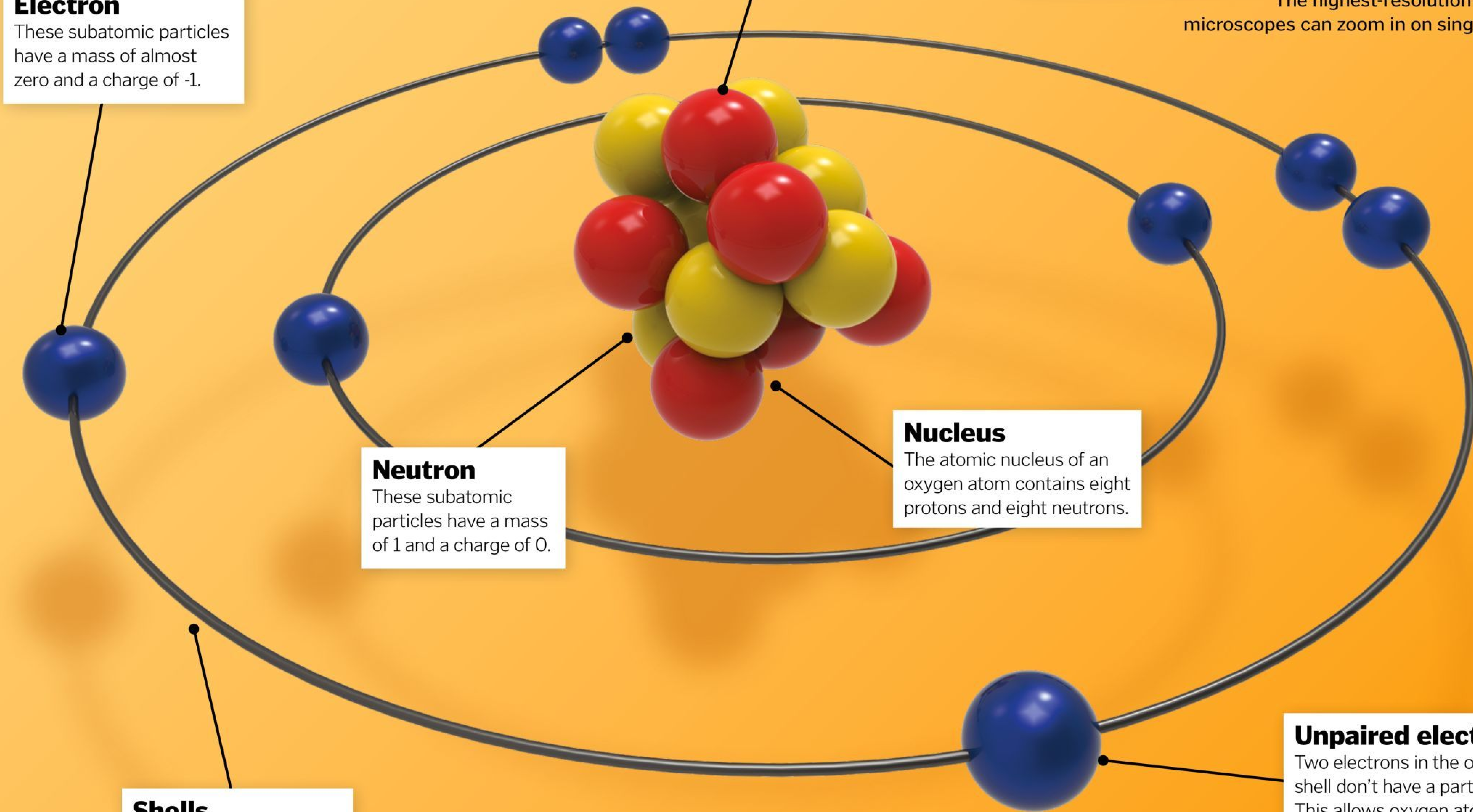
Scale: **1 femtometre**



The highest-resolution electron microscopes can zoom in on single atoms

Anatomy of an atom

Lifting the lid on the subatomic particles that make up the atoms in the air we breathe



Proton
These subatomic particles have a mass of 1 and a charge of +1.

Electron
These subatomic particles have a mass of almost zero and a charge of -1.

Neutron
These subatomic particles have a mass of 1 and a charge of 0.

Nucleus
The atomic nucleus of an oxygen atom contains eight protons and eight neutrons.

Unpaired electrons
Two electrons in the outer shell don't have a partner. This allows oxygen atoms to form chemical bonds.

Shells
An oxygen atom contains eight electrons, arranged into two orbital shells.

ATOM FACTS

118
Number of elements in the periodic table

90
Number of elements that exist in nature in appreciable quantities on Earth

75%
Most of the matter in the universe is hydrogen

2.6 secs

A new chemical is being made with speedy regularity

50 million
CHEMICALS HAVE BEEN DISCOVERED OR MADE BY HUMANS

7,700
The number of chemicals currently in use in industry

Stars made all of the elements heavier than hydrogen and helium

covalent bonds, or they can steal electrons from one another to form ionic bonds.

Covalent bonds are common inside our own bodies. Carbon atoms need four electrons to complete their outer shell, so they share with up to four other atoms, including other carbons. This makes them perfect for forming large biological molecules like DNA.

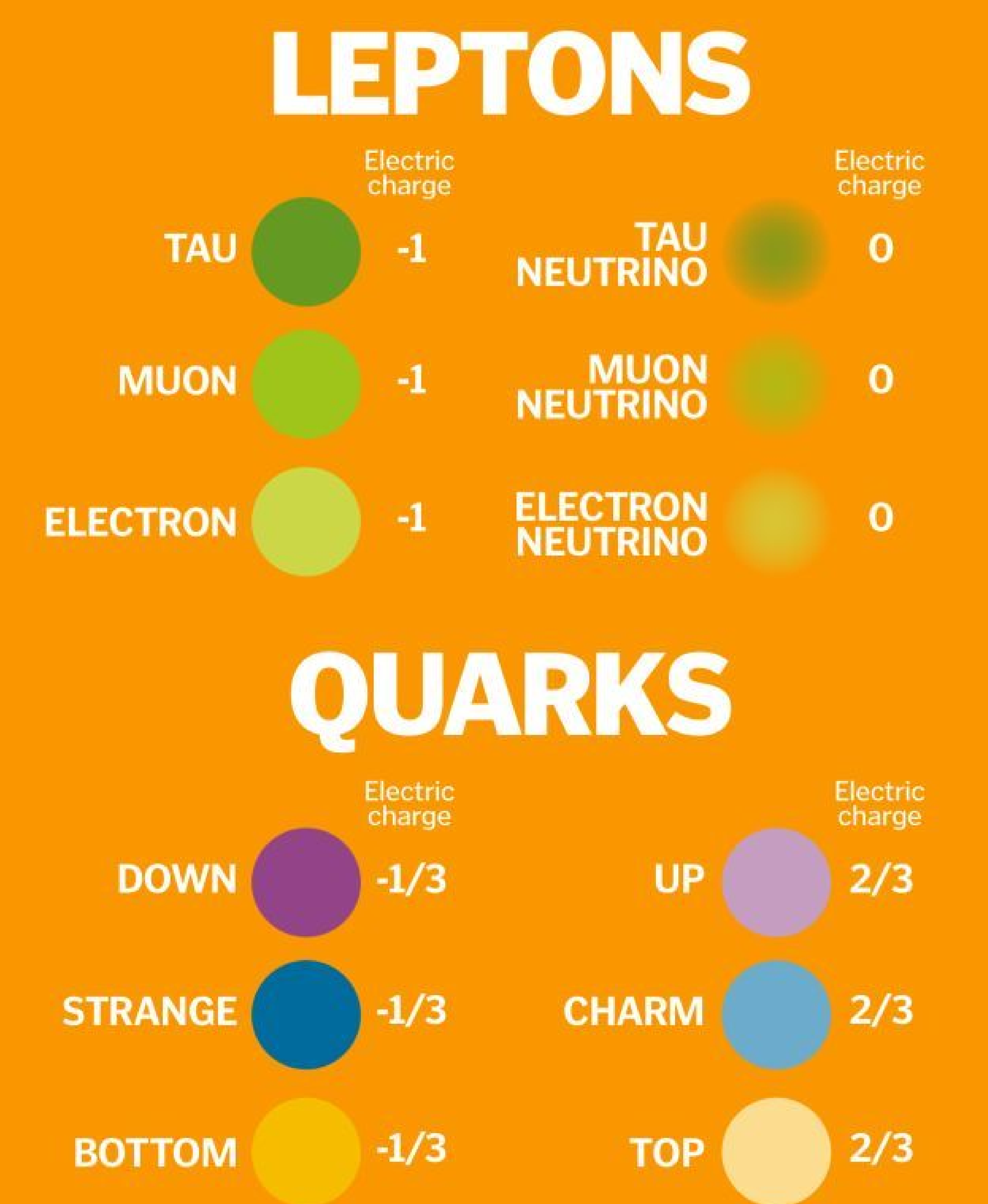
Ionic bonds are more commonly found in the ground. They happen when a non-metal steals electrons from a metal, becoming negatively charged. At the same time, the metal becomes positively charged. These ions attract one another, sticking together in repeating structures, like salt crystals.

> *"They can share their electrons to form covalent bonds, or they can steal electrons"*

Bonds between atoms can break and reform, allowing the elements to perform some amazing chemical tricks. They combine to produce larger compounds, decompose to form smaller ones, or swap one element for another to produce a chemical with different properties. These dynamic interactions are happening all around us, all the time.

Smaller still

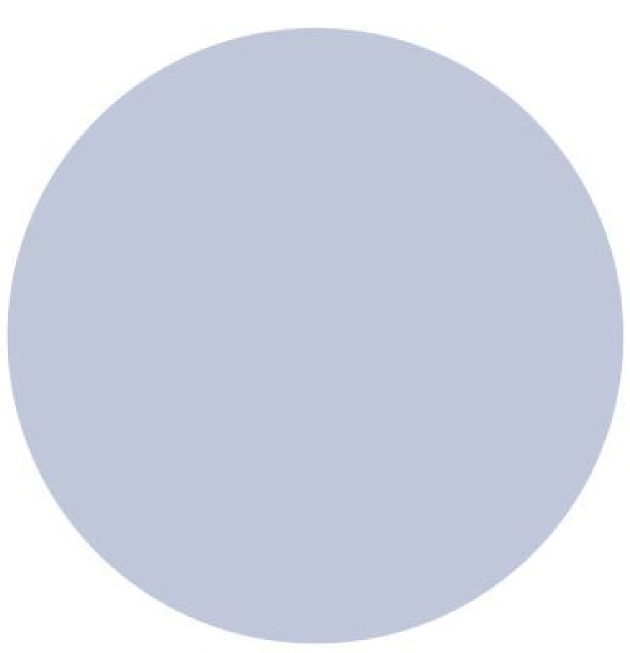
The protons and neutrons that make up the atomic nucleus aren't the smallest components of matter. These are the 'elementary particles' – quarks and leptons. There are six types of quark, arranged into pairs: up and down, charm and strange, top and bottom. They have a partial electrical charge and a 'colour charge' of red, green or blue. There are also six types of lepton: electron, muon, tau and their associated neutrinos. It takes four particles to make up the simplest hydrogen atom: two up quarks and one down quark for the proton and one electron to orbit around the outside. The most common form of hydrogen has no neutrons.



There are six quarks and six leptons, each with different properties

Atomic evolution

Our understanding of atomic structure has come a long way in the past 200 years

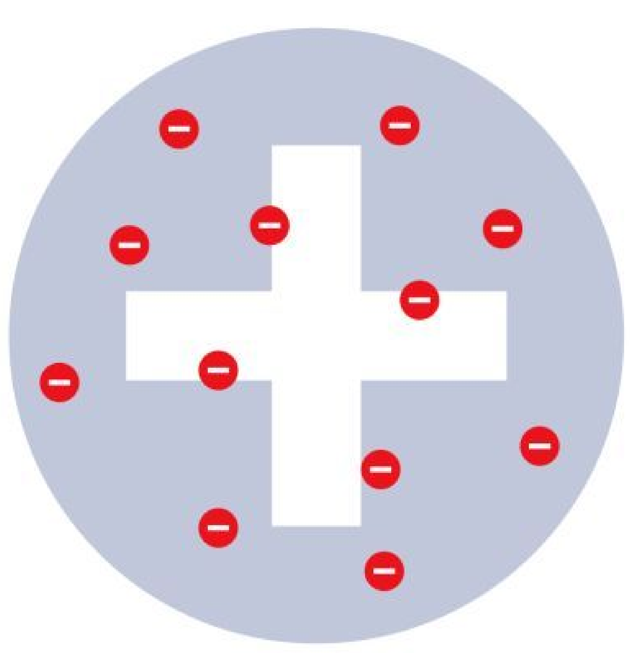


1803 Solid sphere

John Dalton was the first to describe atoms. The word came from the ancient Greek 'a', meaning 'not', and 'temnein', meaning 'to cut'. He thought that they were indivisible.

ACCURACY

Dalton recognised that different types of atom had different properties. But he didn't realise they contained smaller subatomic particles.

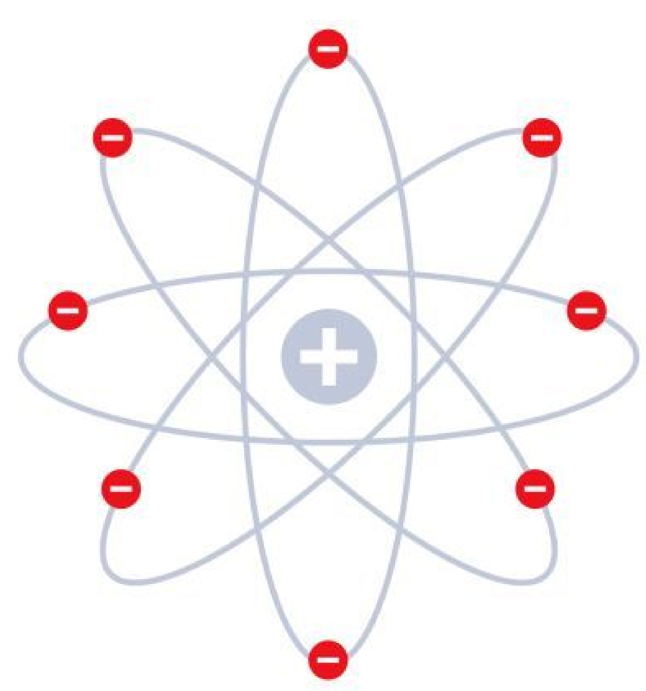


1904 Plum pudding

J.J. Thomson discovered electrons and made a new model of the atom to include them. He stuck them inside a sphere of positive charge, like fruits in a cake.

ACCURACY

This model recognised that atoms contained smaller components, including electrons. But the structure was wrong; the atomic nucleus was missing.

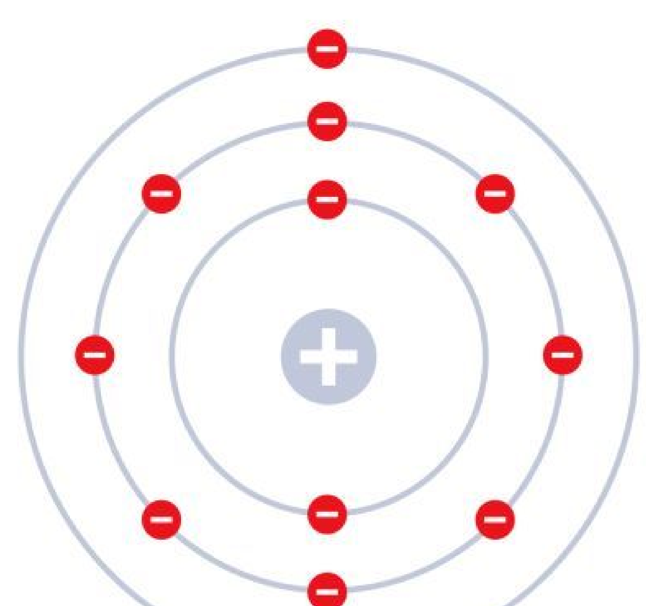


1911 Nuclear

When Ernest Rutherford tried firing tiny particles at atoms, most passed through. This revealed that most of the atom is empty space, with a small nucleus at the centre.

ACCURACY

A positive nucleus surrounded by negative electrons is close to our modern understanding of atoms. But Rutherford hadn't quite captured how electrons move.

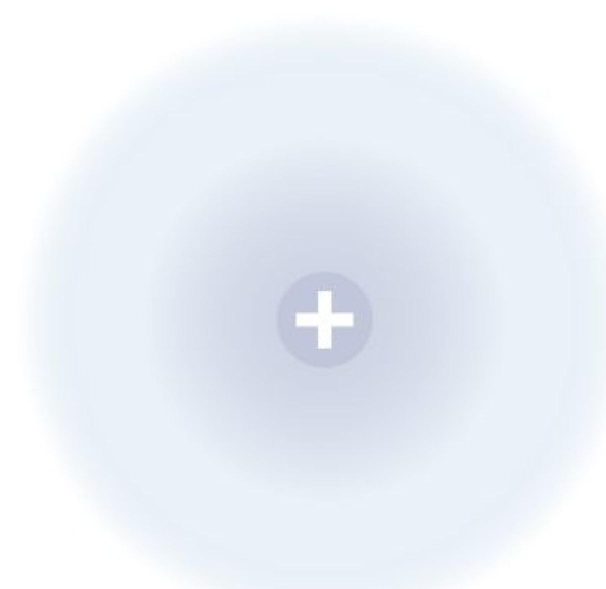


1913 Planetary

Niels Bohr's planetary model describes electrons travelling in orbits called 'shells'. They are a fixed distance from the nucleus and have a fixed energy level.

ACCURACY

The planetary model explains why small elements absorb and emit certain frequencies of radiation. However, it runs into problems as elements get heavier.



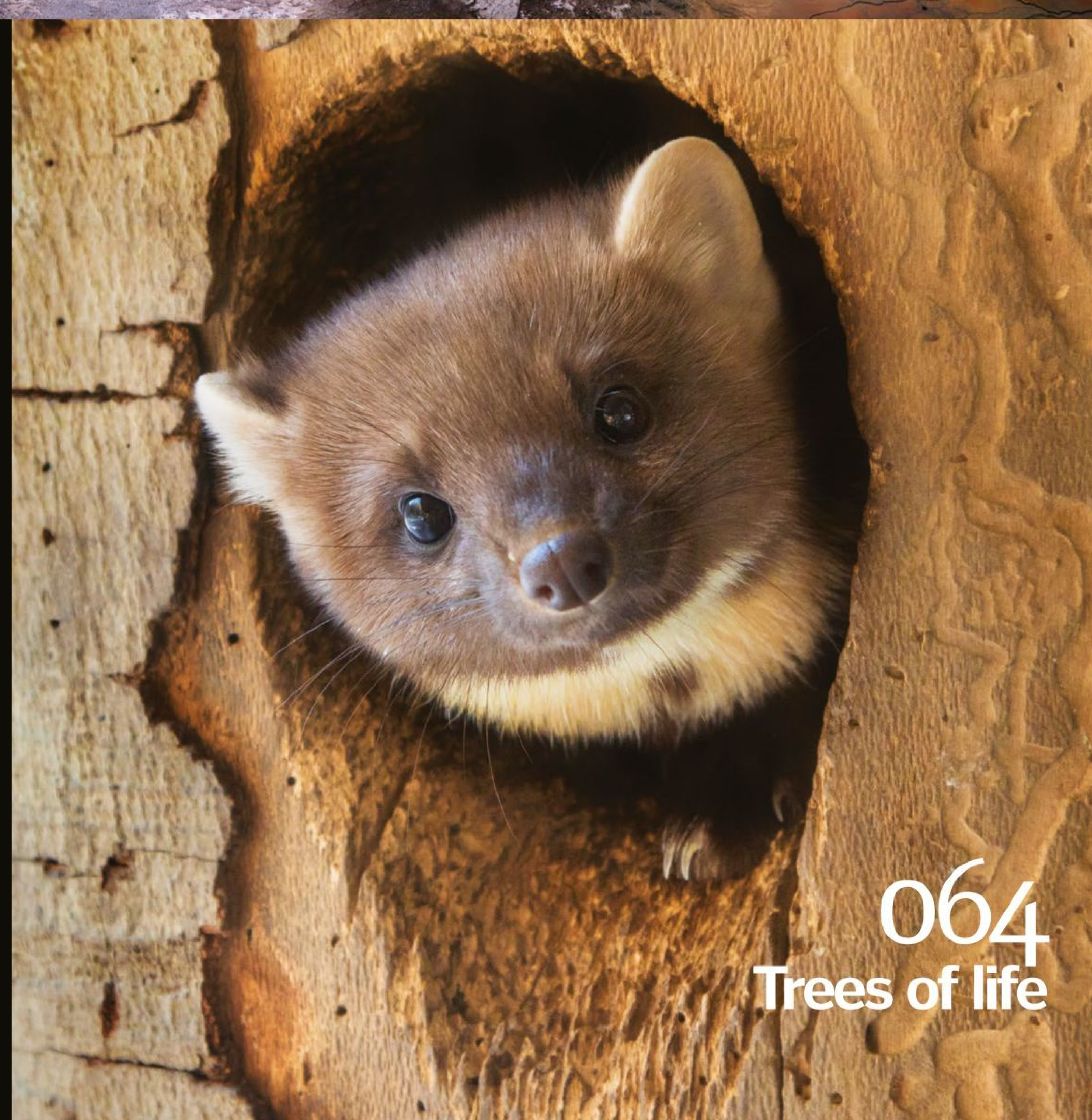
1926 Quantum

Rather than think of orbitals as circular paths, Erwin Schrödinger imagined them as probability clouds. There is a 90 per cent chance of finding an electron somewhere inside its orbital.

ACCURACY

This model is the most up to date. Thinking of electrons as waves in clouds of probability helps to explain the behaviour of subatomic particles.

ENVIRONMENT



DID YOU KNOW? *Dwelling in hydrothermal vents, the bacteria Pyrolobus fumarii requires temperatures of over 90°C to survive*

LIFE AT THE EXTREME

From volcanic ocean vents to the tops of the Himalayas, extremophiles have found ways to conquer every corner of the planet

Words by **Victoria Williams**

Although a few organisms with staggering survival skills have been known to us for centuries, the term 'extremophile' was first coined in 1974 by a scientist called R D MacElroy. It means 'extreme-loving' and refers to any form of life that thrives outside the narrow band of conditions humans can tolerate. Extremophiles have only been studied in detail for the last few decades, but they've already challenged many ideas we have about life and its limits.

Most extremophiles belong to the domain Archaea. These organisms consist of a single cell without a nucleus, and they're believed to be the oldest life forms on Earth, dating back billions of years. It's little surprise that these ancient species are the most tolerant and adaptable, since the young planet would have been a volatile and extreme place enveloped by a toxic atmosphere.

Today, extremophiles can be found all over the world in the most inhospitable environments; even the most desolate landscape is likely to be teeming with life invisible to the naked eye.

THERMOPHILES

In pools and springs hot enough to cause severe burns and even death to humans you'll find thermophiles feeding on the sulphur and ammonia in the blistering water. These microbes often produce pigments and lend their bright colours to the edge of the water. Heat-loving organisms have fatty acid linings in their cell membranes to stop them disintegrating at high temperatures.

At the bottom of the ocean, vents known as black smokers send out plumes of water and minerals reaching 400 degrees Celsius in temperature. The liquid doesn't boil because of the immense pressure it's under from the water above, but it still seems like the last place creatures would choose to live. Amazingly, it's not just microorganisms that can bear to be around these cracks in the

> "An extremophile is any form of life that thrives outside the narrow band of conditions humans can tolerate"

Earth's surface; busy ecosystems develop and flourish around them, sustained by the nutrients leaking out from the planet's crust. Bacteria are the first to track down a new vent, followed by hardy bivalves like clams. Larger creatures like tubeworms and lobsters move in later, creating unusual communities that have amazed scientists since they were discovered in the 1970s.

CRYOPHILES

Frigid water, permafrost, mountain peaks and expanses of ice are havens for cryophiles. These organisms live in parts of the world that remain permanently cold and can withstand temperatures well below freezing, with some unicellular species still active at -25 degrees Celsius. Cryophiles, ranging from bacteria to deepwater fish, often produce antifreeze proteins to prevent ice crystals from forming in their bodily fluids.

As well as the freezing temperatures, cryophiles must contend with other stresses like high pressure and low oxygen levels on the seabed and high salinity in sea ice. When times get really tough, some cold-dwellers shut down their bodies and enter a state of dormancy until conditions become more tolerable again.

ACIDOPHILES AND ALKALIPHILES

While humans are best suited to a neutral pH between 6.5 and 7.5, acidophiles flourish in acidic environments where the pH is 5 or lower. Strong cell membranes keep them safe from the potentially damaging effects of acid, allowing them to live in sulphuric pools, polluted water and even human stomachs. Some aggregate for extra protection, forming slimy colonies called biofilms.

Alkaline conditions, at the other end of the scale, can be just as challenging. Alkaliphiles like *Spirochaeta americana* – bacteria found

> "Busy hydrothermal ecosystems are sustained by the nutrients leaking out from the planet's crust"

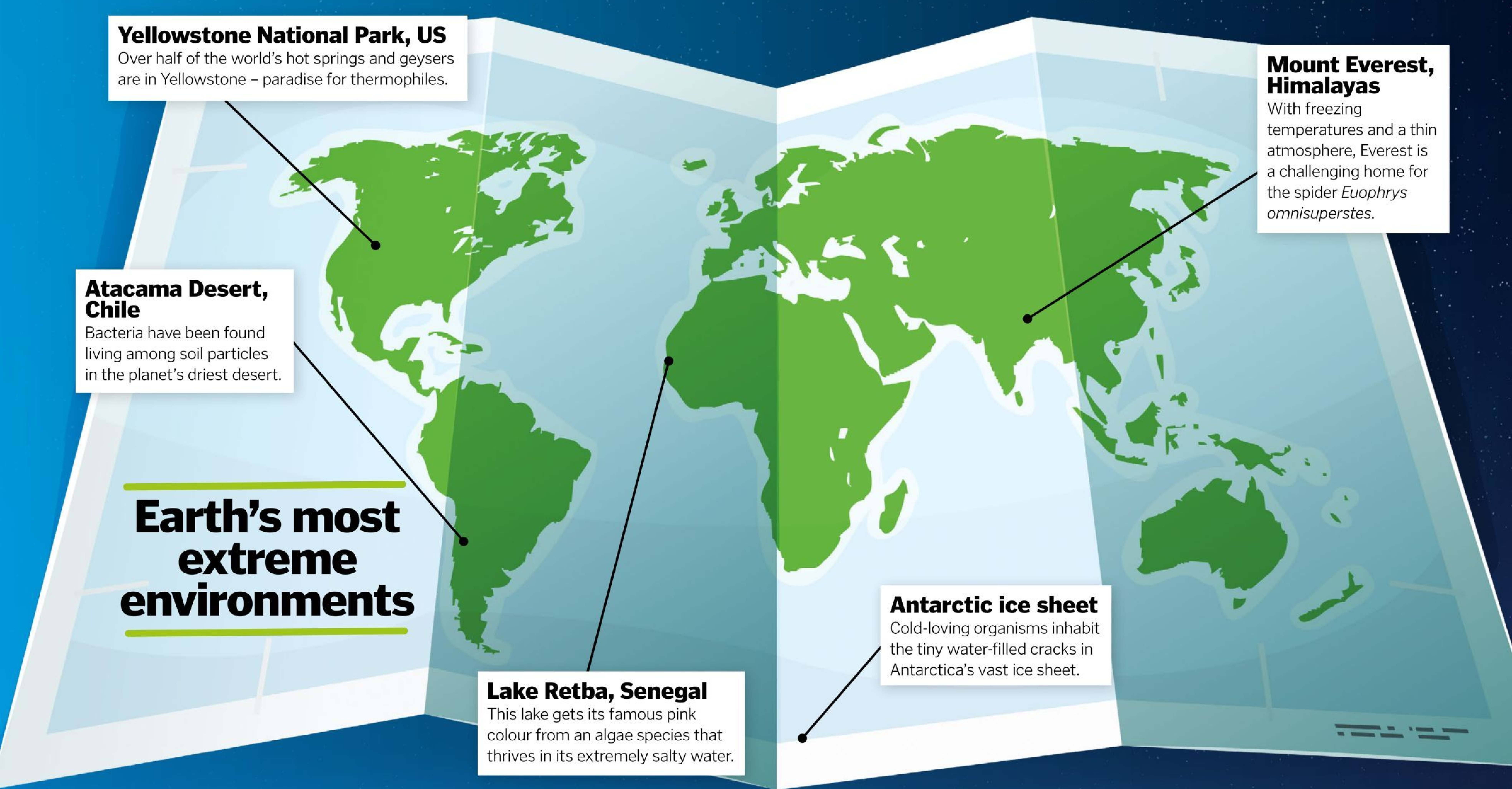
Extreme enzymes

Enzymes are protein molecules that act as catalysts for chemical reactions in the body, and they're vital for keeping processes running smoothly. Most enzymes lose their structure and stop functioning – a process known as denaturing – when they reach the limits of their optimal ranges of temperature, salinity and pH. Extremophiles, however, have specialised enzymes, known as extremozymes, which are as well adapted to extreme environments as they are. For example, thermophile enzymes are compact, with a tightly wound structure to ensure they hold their shape under the effects of high temperature.

Extremozymes have been harnessed for use in industrial processes. While most enzymes can't cope with the harsh conditions, those derived from extremophiles work well and catalyse reactions to make the processes more efficient. Used in the manufacture of products from food to fuel, the global market for industrial enzymes has rapidly grown to billions of dollars.

Industrial enzymes have become big business

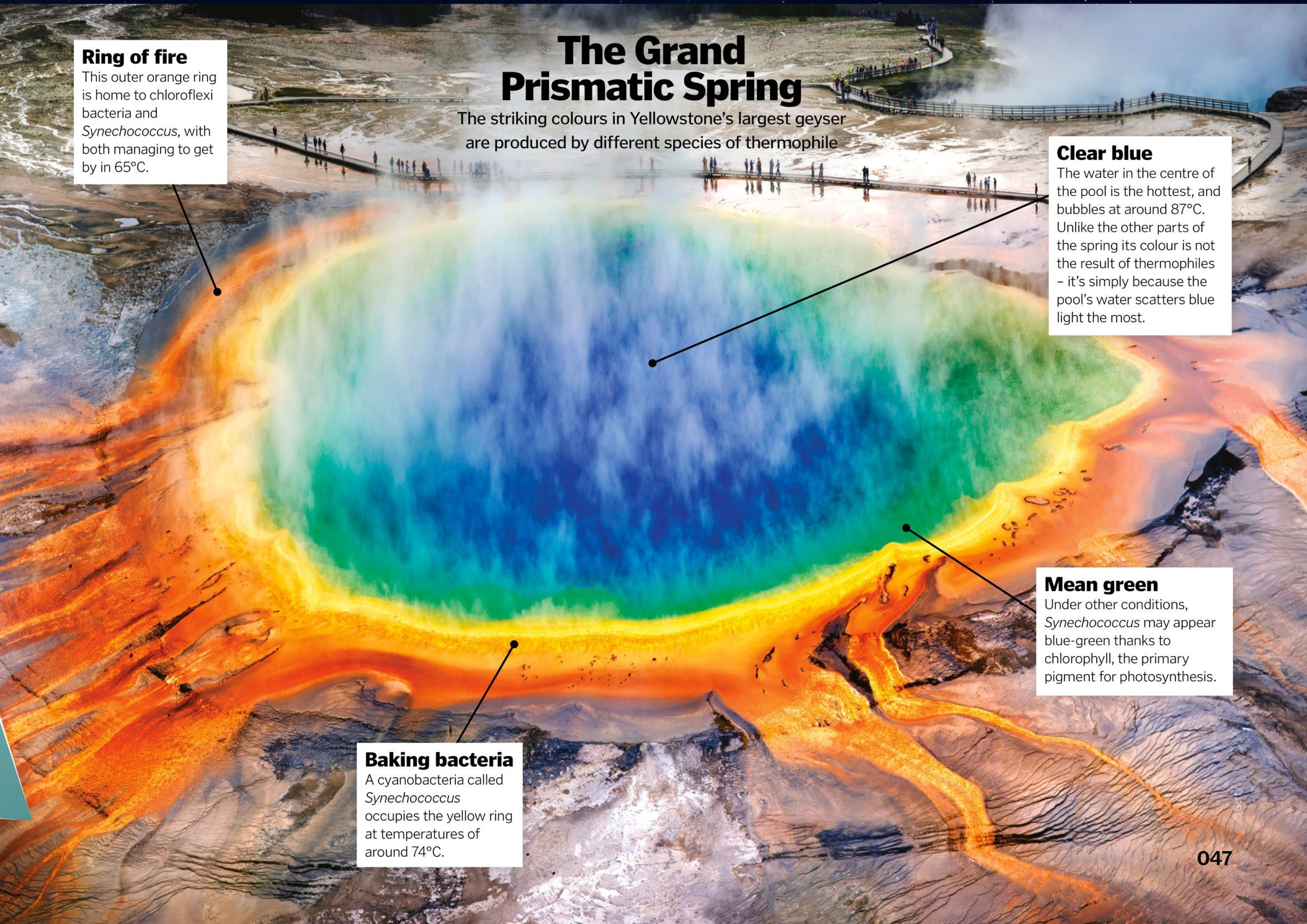
Earth's most extreme environments



DID YOU KNOW? *A bacteria called Halobacterium salinarum thrives in the salty waters of the Dead Sea*

Bacteria even inhabit the Atacama Desert, a region that receives an average of just 15 millimetres of rain each year

The bright colours of Yellowstone's Morning Glory Pool are also the result of bacteria



The Grand Prismatic Spring

The striking colours in Yellowstone's largest geyser are produced by different species of thermophile

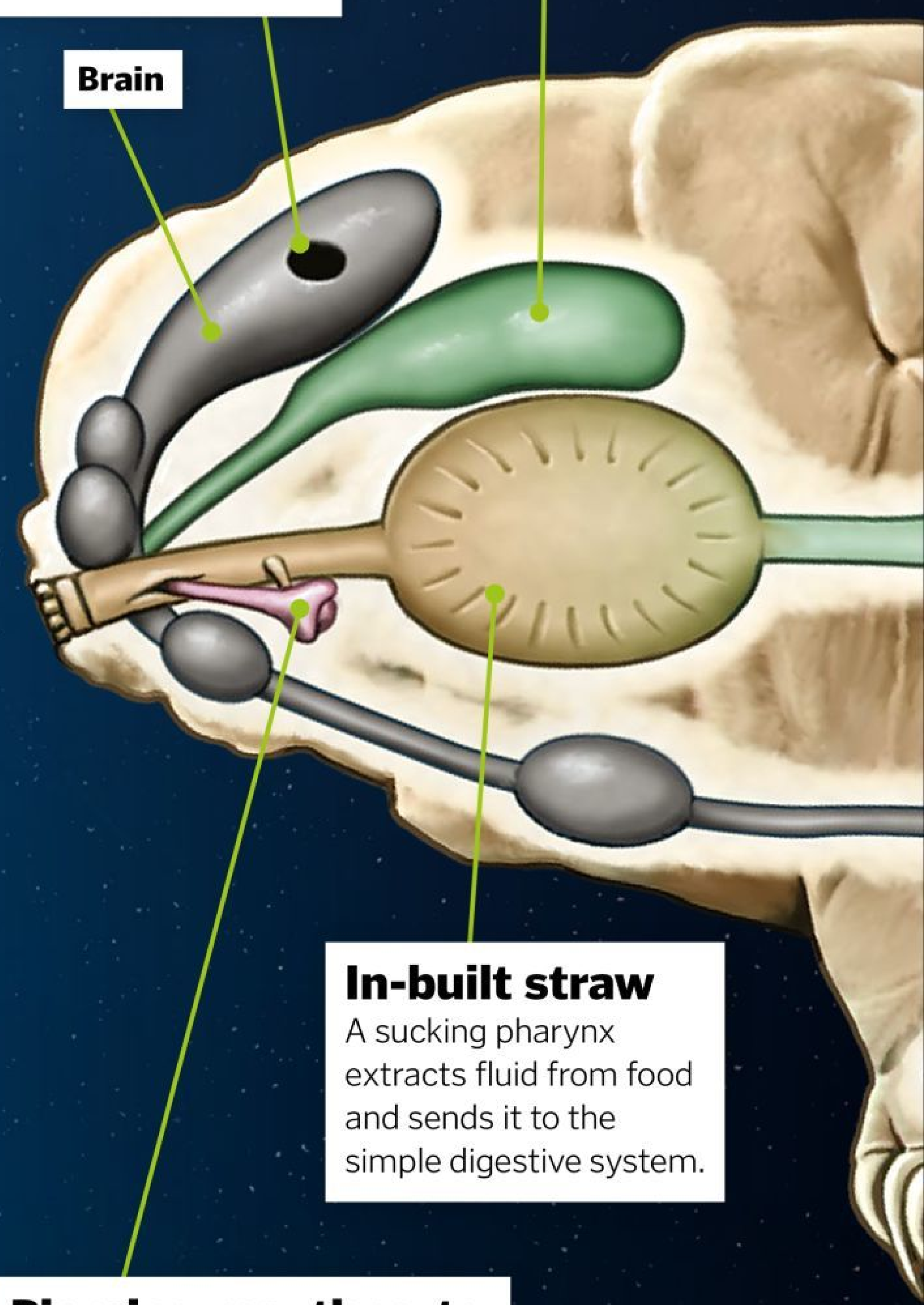
Ring of fire
This outer orange ring is home to chloroflexi bacteria and *Synechococcus*, with both managing to get by in 65°C.

Clear blue
The water in the centre of the pool is the hottest, and bubbles at around 87°C. Unlike the other parts of the spring its colour is not the result of thermophiles – it's simply because the pool's water scatters blue light the most.

Mean green
Under other conditions, *Synechococcus* may appear blue-green thanks to chlorophyll, the primary pigment for photosynthesis.

Baking bacteria
A cyanobacteria called *Synechococcus* occupies the yellow ring at temperatures of around 74°C.

The soda cichlid swims happily in the alkaline waters of a soda lake



in salty, mineral-rich mud deposits at Mono Lake in California – cannot survive at a pH lower than 8 and do not need oxygen to respire. By actively driving certain molecules out of their cells in exchange for others, they can produce an internal pH closer to neutral than their surroundings and avoid any damage to their structure.

METHANOGENS

Methanogens are microorganisms that produce methane as a byproduct when their metabolic processes take place in low oxygen levels; living in oxygen-poor swamps and marshes, they're responsible for the bubbling that can be seen at the surface. Most people know that cows produce levels of methane harmful to the environment, but it's a lesser-known fact that the blame for this gas really lies with methanogens inhabiting the animals' guts.

Methane-emitting organisms have been found under kilometres of ice and in desert soil. The discovery of methanogens in arid environments is of particular interest to scientists; some believe that methane detected in the atmosphere around Mars could be a sign of microorganisms living on the Red Planet.

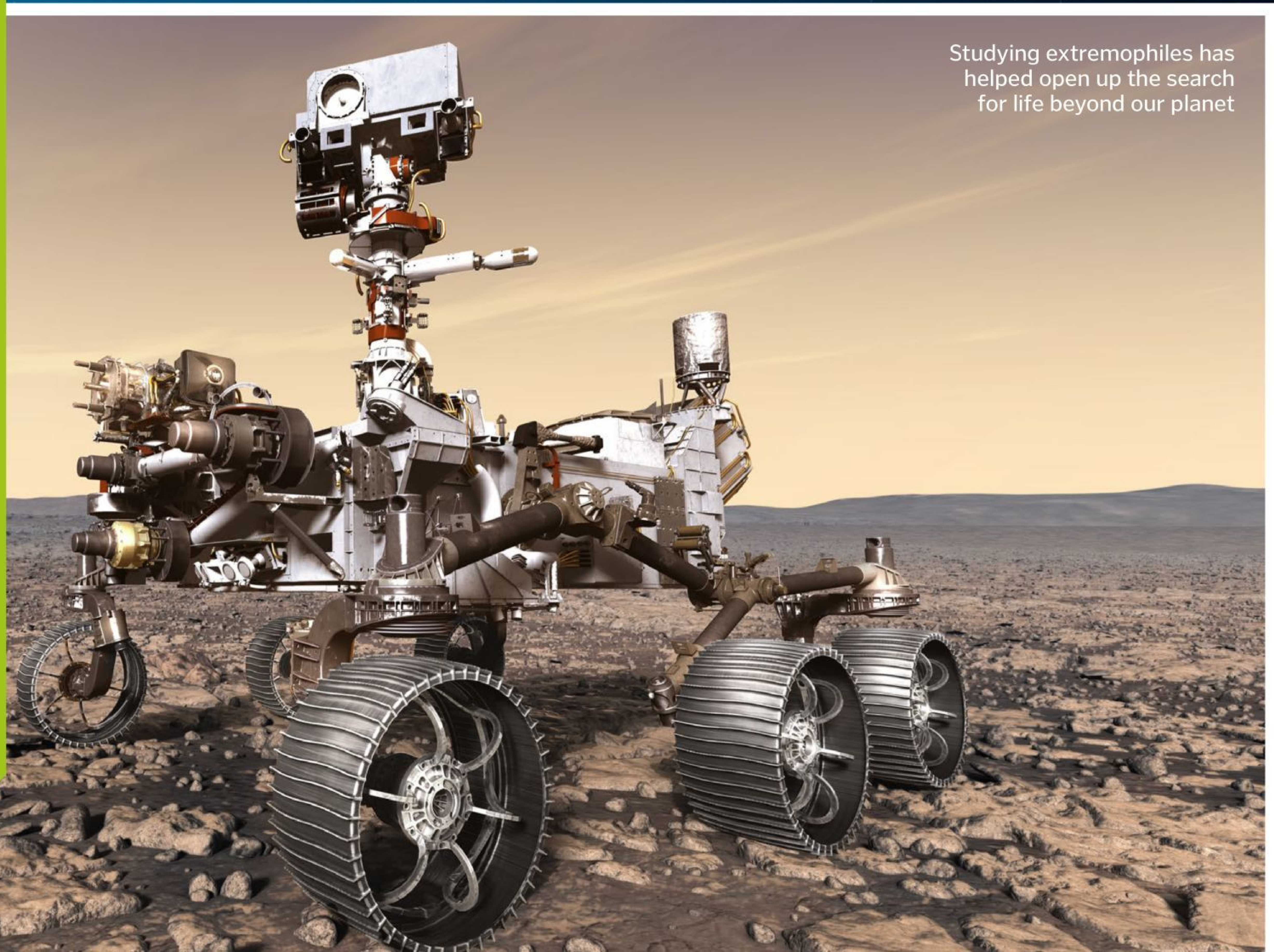
POLYEXTREMOPHILES

Few things in nature are simple or fit into neat categories, and there are extremophiles that require an even longer title than the others because they're adapted to live with multiple stressors. Take *Desulforudis audaxviator*; this bacteria lives 2.8 kilometres underground in groundwater in a South African gold mine, where it survives on chemicals released by the decay of minerals

Inspiring space exploration

For hundreds of years humans have been debating the possibility of extraterrestrials, and more recently we've started looking for signs of life on other planets. Extremophiles – especially those able to live with more than one extreme factor in their environment – live in parts of the planet most like the harsh landscapes found elsewhere in the galaxy and give scientists an idea of what extraterrestrial organisms might look. The study of Earth's toughest deepwater creatures to help predict what we might one day meet in a dark corner of space was even the focus of a James Cameron film called *Aliens of the Deep*.

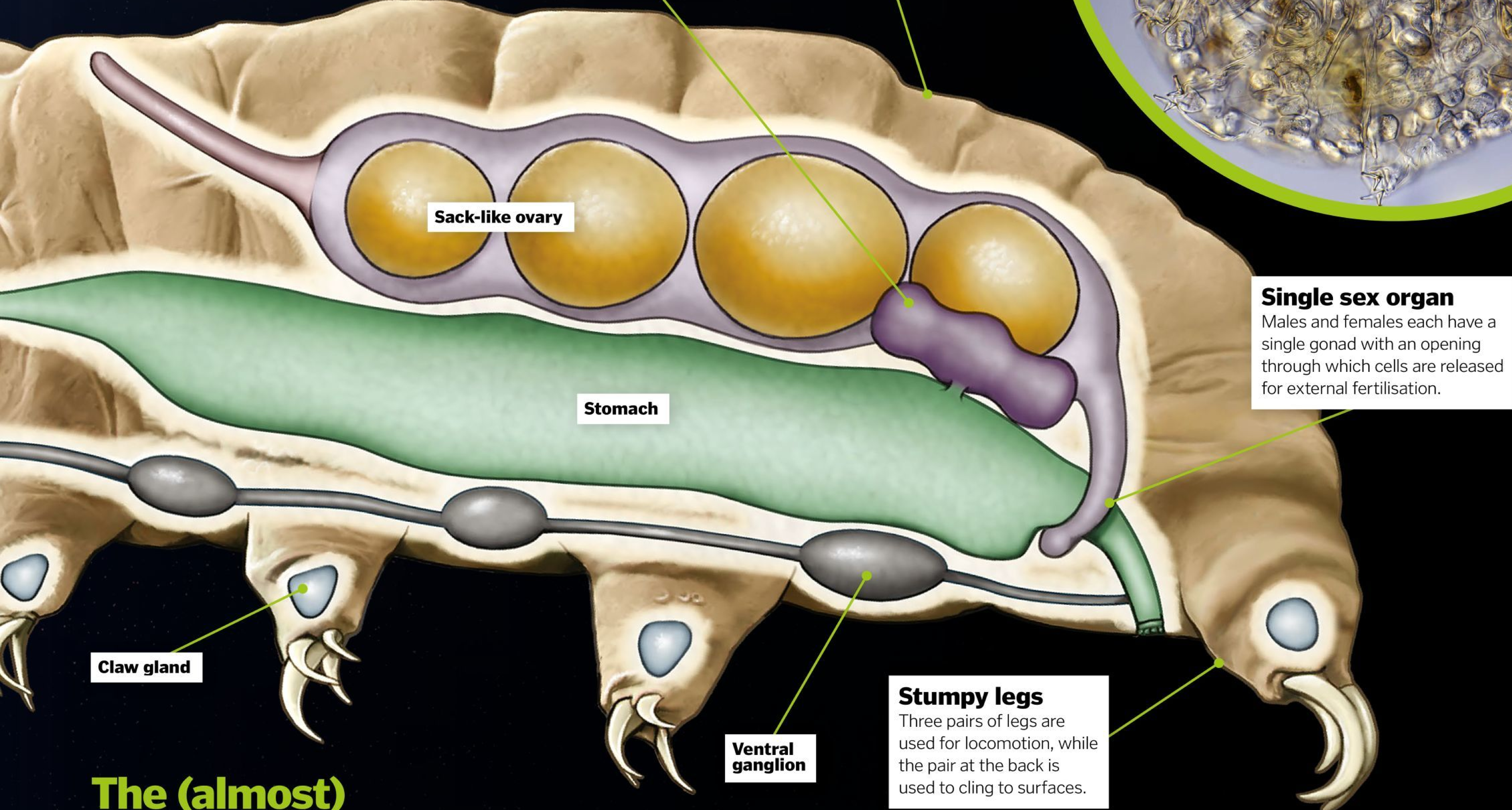
Species of extremophile have been discovered in dark and oxygen-deprived subterranean ecosystems in recent years, expanding the area of a Solar System that could be suitable for hosting life and widening the search for proof that we're not alone in the universe.



Studying extremophiles has helped open up the search for life beyond our planet

Built for survival

It might be simple, but the tardigrade's tiny body is the perfect survival pod



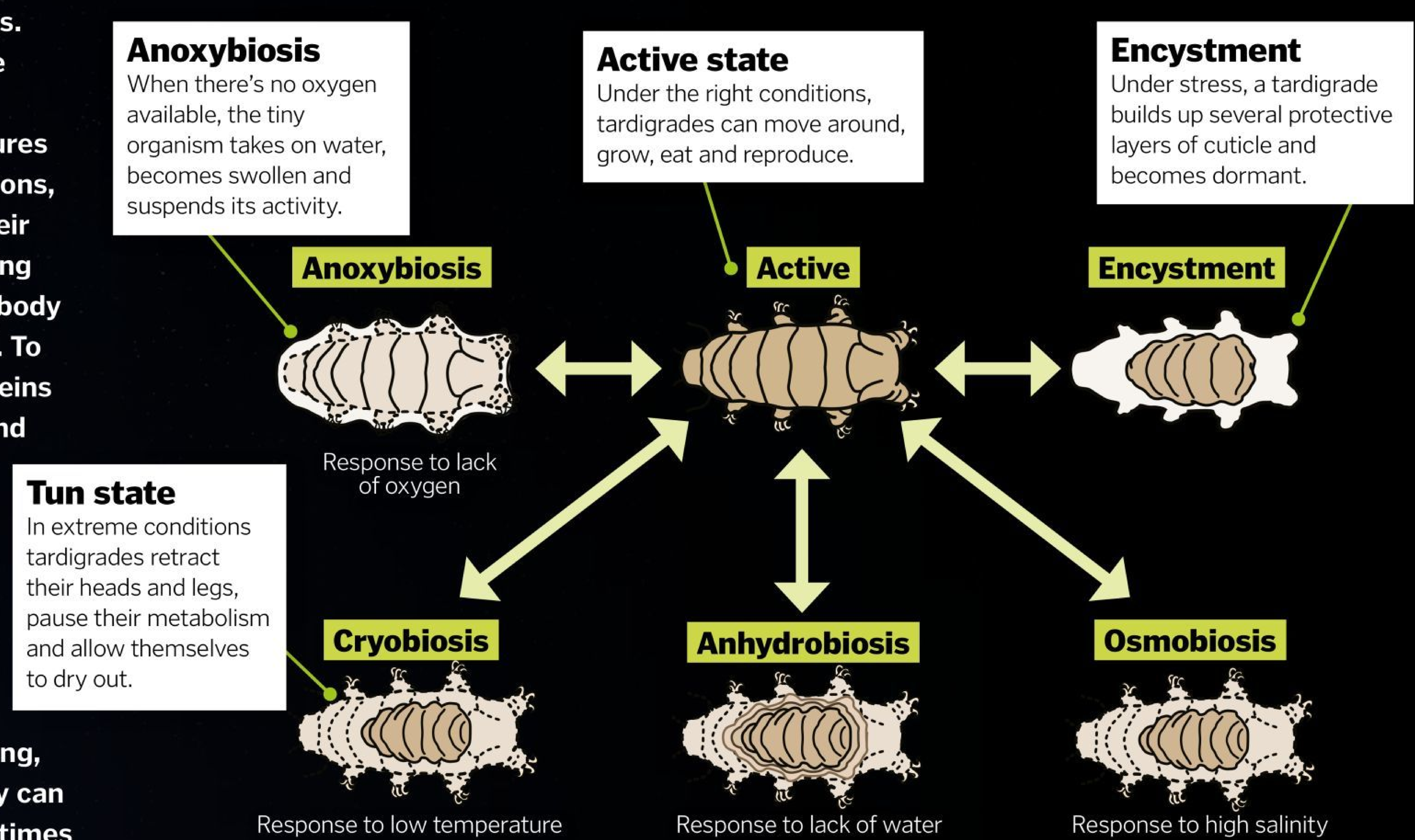
The (almost) indestructible water bear

Tardigrades, microscopic water-dwelling animals also known as water bears, are among the most famous survivalists in the world. Since they were first described by a German zoologist in 1773 they've been found in the depths of the ocean, at the top of Himalayan mountains, at the poles and in hot springs.

Despite this amazing resilience, they're technically not extremophiles. This classification is reserved for those creatures that exploit and thrive in extreme conditions, while tardigrades cope by suspending their metabolism and entering dormancy. During periods of drought, water content in the body drops to one per cent of the normal level. To prevent damage to the body, unique proteins take the place of lost water in the cells and become glass-like. In their dehydrated tun state some species of tardigrade are capable of enduring temperatures close to absolute zero and, though hot temperatures will eventually kill them, they can last for several minutes at 150 degrees Celsius.

With their metabolism barely functioning, starvation can be endured for years. They can also survive radiation levels hundreds of times higher than the dose that would kill a human and have even returned alive from a journey to the vacuum of space.

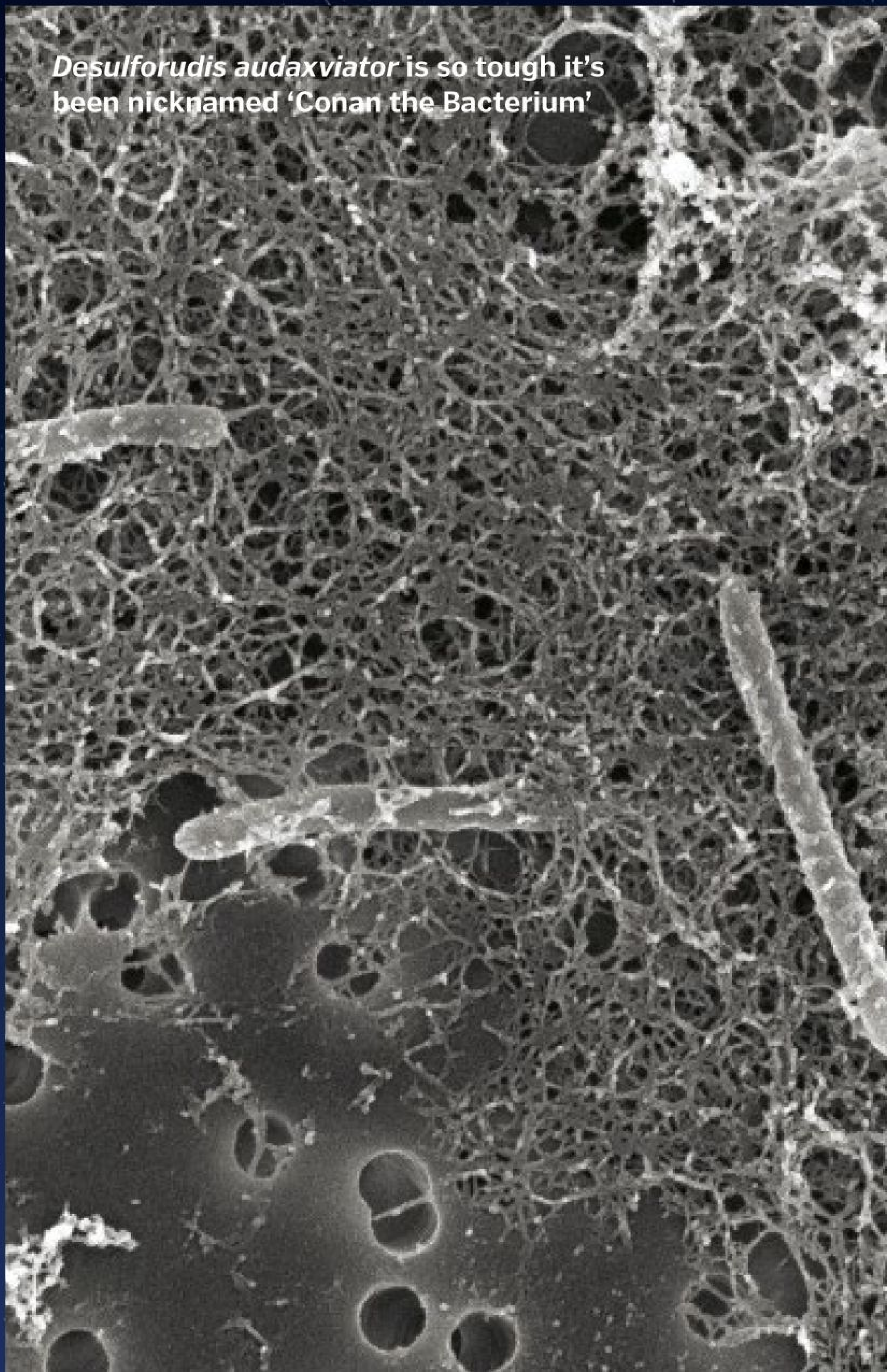
Many tardigrades can survive in this desiccated dormant state (known as cryptobiosis) for five years and will resume normal activity within hours of exposure to moisture. A few exceptional specimens have been 'brought back to life' after almost a decade, establishing tardigrades as some of the creatures most likely to survive a nuclear war or apocalyptic astrophysical event.



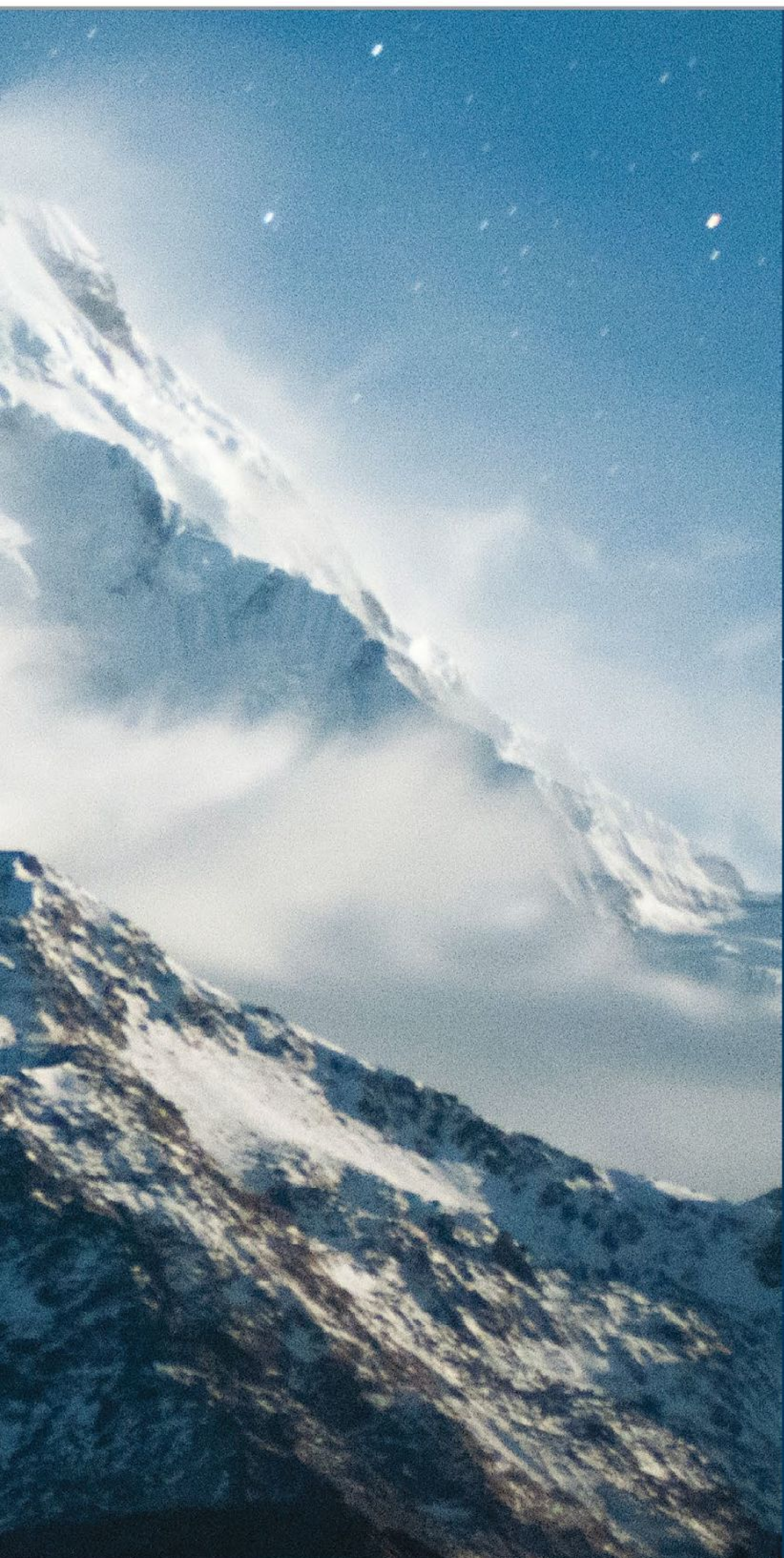
Bacteria and one hardy species of spider call Everest home

The bald notothen is a cod icefish native to the subzero waters around Antarctica

Scientists are studying extremophiles to better understand the origins of life and adaptations to extreme conditions



Desulforudis audaxviator is so tough it's been nicknamed 'Conan the Bacterium'



in the rock. The groundwater is old and highly alkaline, and temperatures in the mine can reach 60 degrees Celsius.

D audaxviator is the only known species that doesn't share its ecosystem with any other life form, and it's among just a few organisms that survive in the complete absence of light and oxygen. The name 'audaxviator' is a nod to its isolated subterranean life – it's part of an inscription found by the hero of Jules Verne's novel *Journey to the Center of the Earth* and means 'bold traveller'.

> "The world's toughest bacterium may help us develop a treatment for radiation exposure"

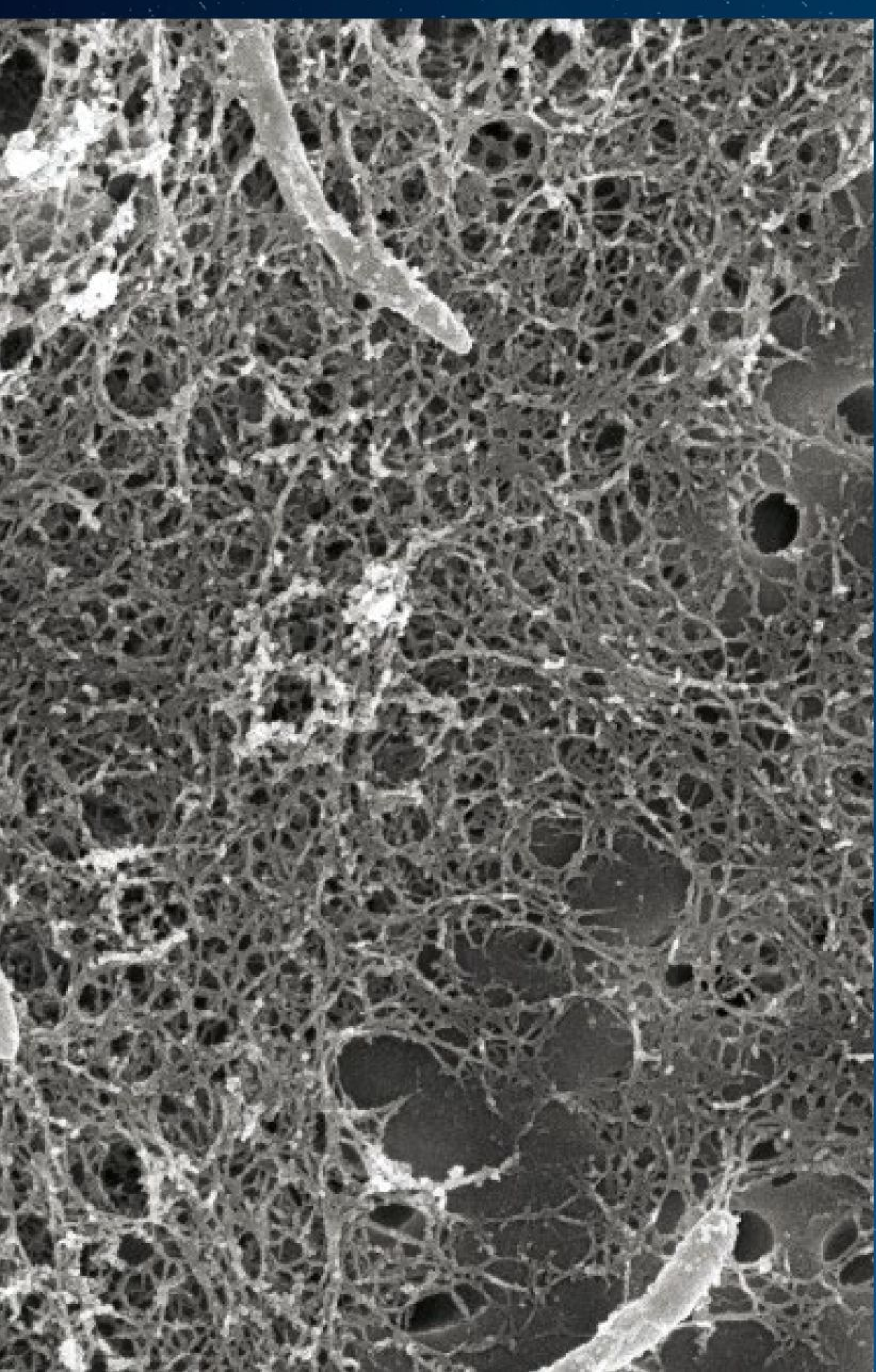
EXTREMOPHILES AND THE FUTURE

One of the reasons extremophiles are so exciting is that we still know relatively little about them. Every study into the hardy organisms reveals something new about their biology or the potential applications they could have in our lives. One extremophile found in stagnant water in an American cave system showed potential to destroy breast cancer cells. Another, *Deinococcus radiodurans*, is listed in the *Guinness Book of World Records* as the world's toughest bacterium; it's radiation- and acid-resistant and can survive vacuums and extreme cold. Its resistance to radiation is due to a set of antioxidants that protect its proteins, and researchers hope this knowledge will lead to the development of a recovery pill for people who have been exposed to radiation. On top of this, it produces proteins that emit infrared light. Scientists believe these fluorescent proteins could be used to light up cells and organisms and allow them to watch the processes taking place inside them for longer than is possible with the jellyfish proteins currently used by medical researchers and biologists.

Extremophiles were around when the planet was still forming and cooling, and they might hold some of the secrets to protecting it. Since they thrive in the most hostile parts of the planet, they have evolved to use whatever is around them. Organisms like those that rely on iron to digest food have the potential to remove harmful metals and industrial waste products from the environment.

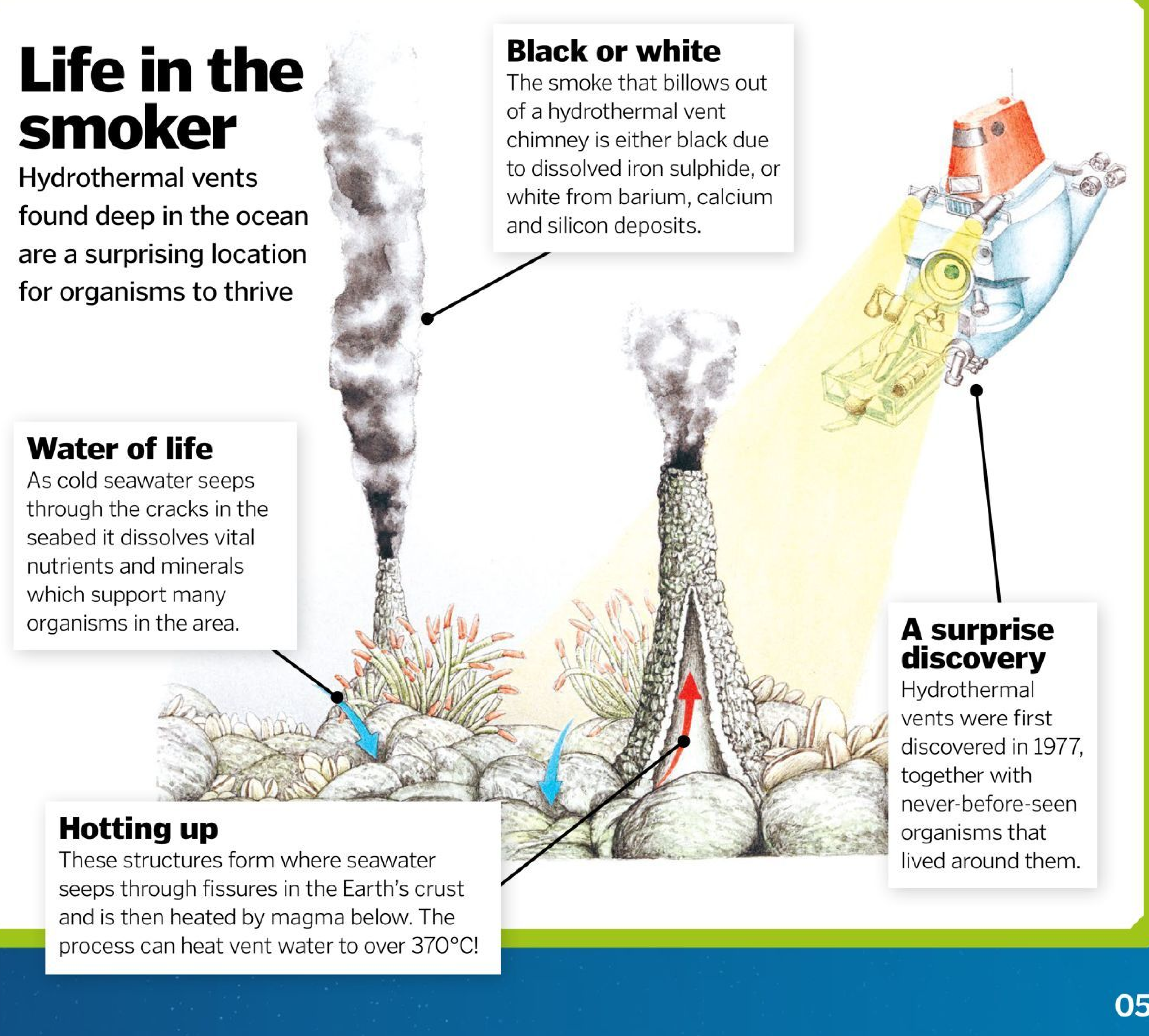
One microorganism discovered in Rotorua, New Zealand, in a geothermal field known as 'Hell's gate' prefers acidic conditions and survives solely on a diet of methane. This species could one day be used to reduce gas emissions from landfill sites and thereby help in the fight against global warming.

Given the rate at which they're now being discovered and the variety of abilities they possess, tiny extremophiles could soon be taking a big step into the spotlight.



Life in the smoker

Hydrothermal vents found deep in the ocean are a surprising location for organisms to thrive




Grey foam-nest tree frogs spend more time in the trees than in the water

The foam-nest frog

Many legs make light work of these frothy egg holders

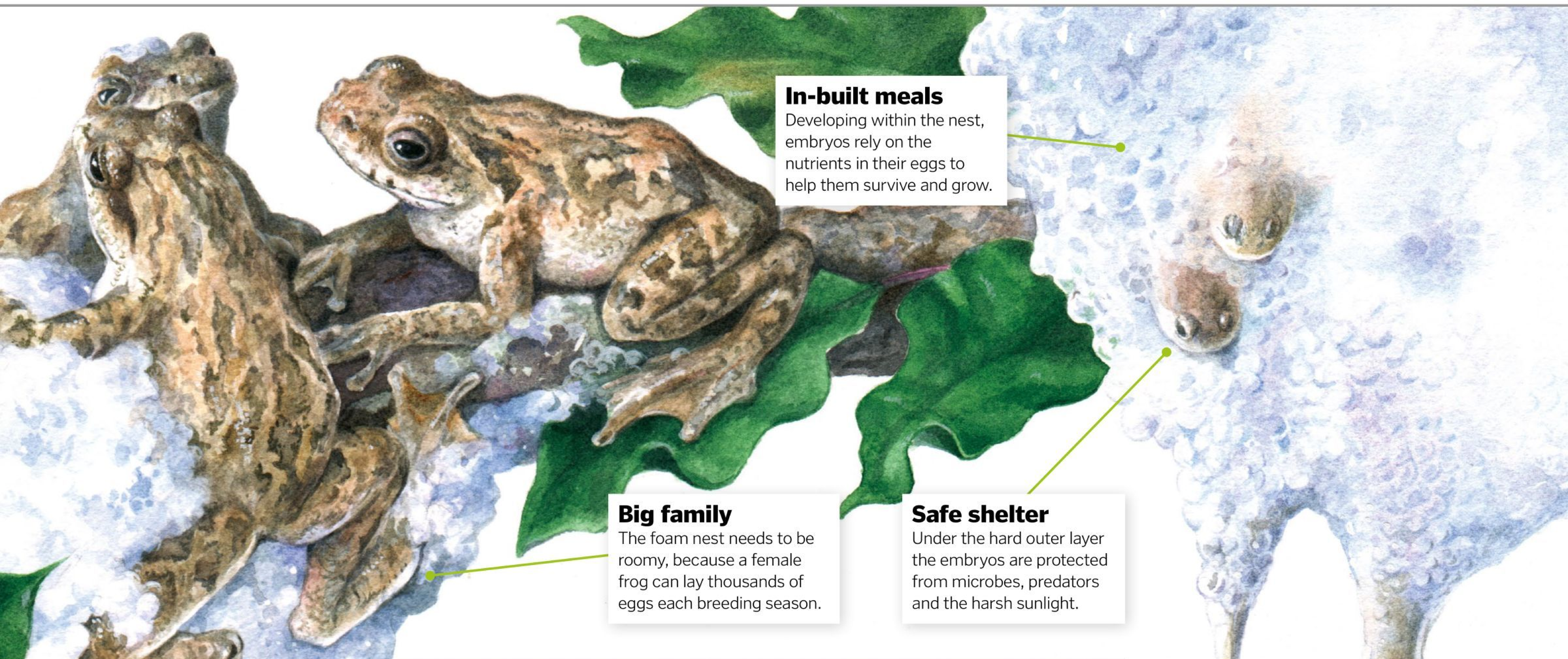
Grey foam-nest tree frog
Chiromantis xerampelina
Class Amphibia
Territory Central, Eastern and Southern Africa
Diet Insects
Lifespan Unknown
Adult weight Unknown

Chiromantis is a genus of frog found in Southeast Asia and the sub-Saharan tropics of Africa. These frogs are known as the foam-nest tree frogs because of the impressive frothy structures they create when rain signals the start of the breeding season.

While the foam nests may appear simple in comparison to other feats of animal architecture, they have some peculiar properties, and, in the case of the grey foam-nest tree frog, are the work of many determined legs. Their nests are created when a female attracts multiple males, who will compete for access to her. The successful individual will then climb onto her back before she secretes a fluid that she will beat into a foam along with her mate, both frogs using their back legs to whip it up.

When a large nest of bubbles has formed the female begins to lay her eggs, which the male then fertilises. The process of frothing and egg laying can take hours, so the female will have breaks to rehydrate. Other males will by now have arrived to contribute to the fertilisation process. When all her eggs are laid and fertilised the frogs part ways and the foam is left to develop a protective crust.

After four to six days the tadpoles are ready to hatch. The bottom of the nest becomes soft, so the tadpoles are able to wiggle out of their eggs and drop straight into the water below.



In-built meals
Developing within the nest, embryos rely on the nutrients in their eggs to help them survive and grow.

Big family
The foam nest needs to be roomy, because a female frog can lay thousands of eggs each breeding season.

Safe shelter
Under the hard outer layer the embryos are protected from microbes, predators and the harsh sunlight.

"The process can take hours, so the female will have breaks to rehydrate"

Other bubble builders

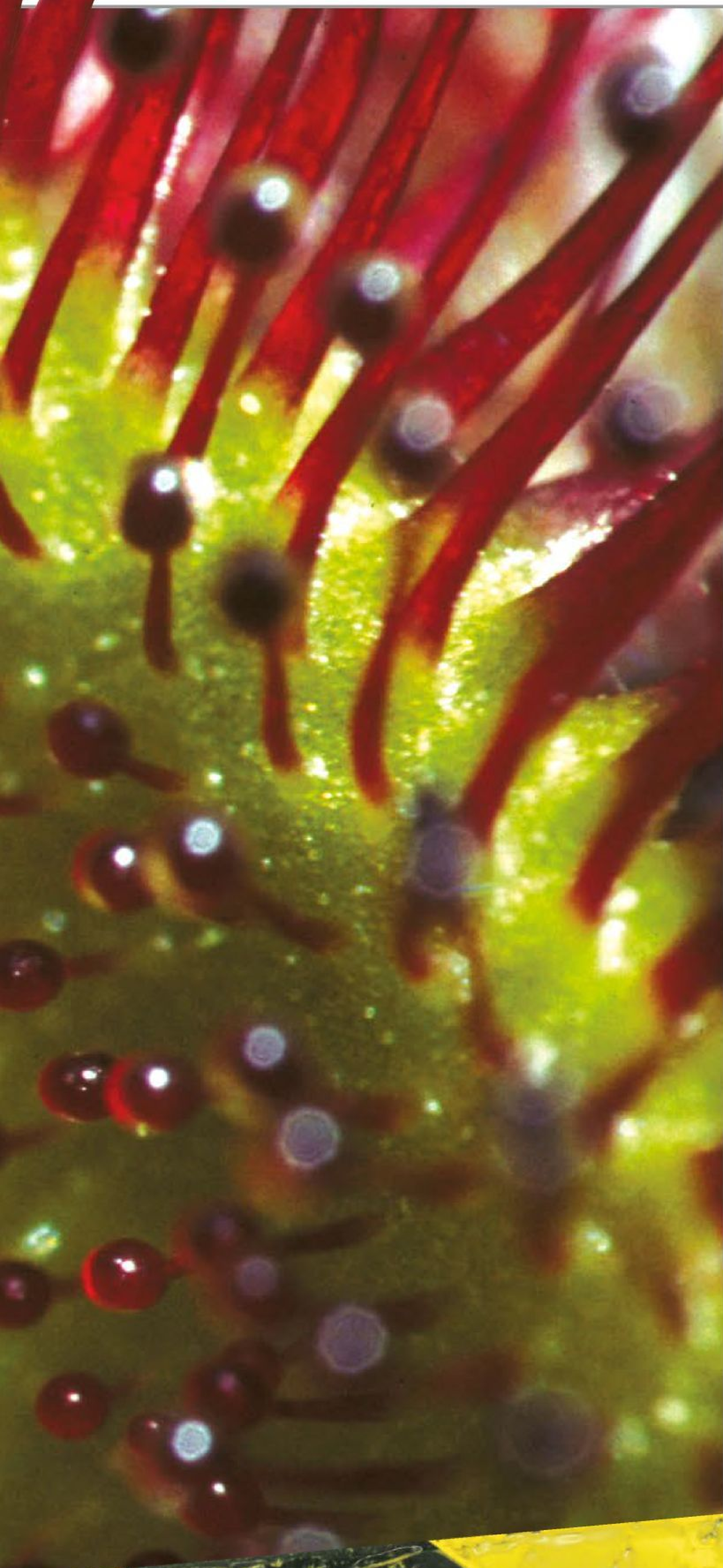
Fighting fish
Males build bubble nests then wait for females to take notice. Eggs are placed among the bubbles to keep them aerated.

Froghopper
Nymphs of this insect family cover themselves in foam made from plant sap. The frothy case hides and hydrates them.

Túngara frog
Female túngaras choose males with attractive calls before the pair whip up floating nests on marshes or ponds.

Waterfront property
The nest is carefully positioned over water so the tadpoles can drop safely when they hatch.

DEADLY PLANTS



Discover the world's most dangerous plants, their poisons and how they 'hunt'

Words by **Scott Dutfield**

Whether they're hiding in the depths of the Amazon or growing in our back gardens, deadly plants have spread their roots across the globe. Because they are physically restricted in their ability to defend themselves against becoming a herbivore's dinner, some have evolved to produce nasty chemical compounds for defence.

Most plants considered 'deadly' to humans and animals use poison to protect themselves. A plant is defined as poisonous by its ability to cause harm or a fatality when eaten or touched by a living organism. Over millennia, poisonous plant species have come up with creative ways to defend themselves, each with their own style. Causing anything from cardiac arrests to blistering skin ulcers, a run-in with the wrong plant can send you to the emergency room.

Deadly plant toxins can be generally classified as having either toxic alkaloids, glycosides, oxalates or proteins – each offers their own nasty consequences when touched or otherwise ingested. One of the most poisonous plants on the planet, oleander, contains a deadly cardiac glycoside that can stop the heart after you've ingested only a single one of the flowering plant's leaves.

Often seen as a favourite at weddings, lily of the valley can damage the heart if eaten

© Getty

Since the toxic chemicals are not used in oleander's biological cycles of growth or respiration, they must be present in the plant for the sole purpose of offering protection. Poisonous plants did not evolve alone, however – driven by the ability to adapt to their environment and its edible bounty, some animal species co-evolved to withstand the deadly nature of some plants. The koala is a common example of a species' ability to negate the toxic powers of its meal, in this case eucalyptus

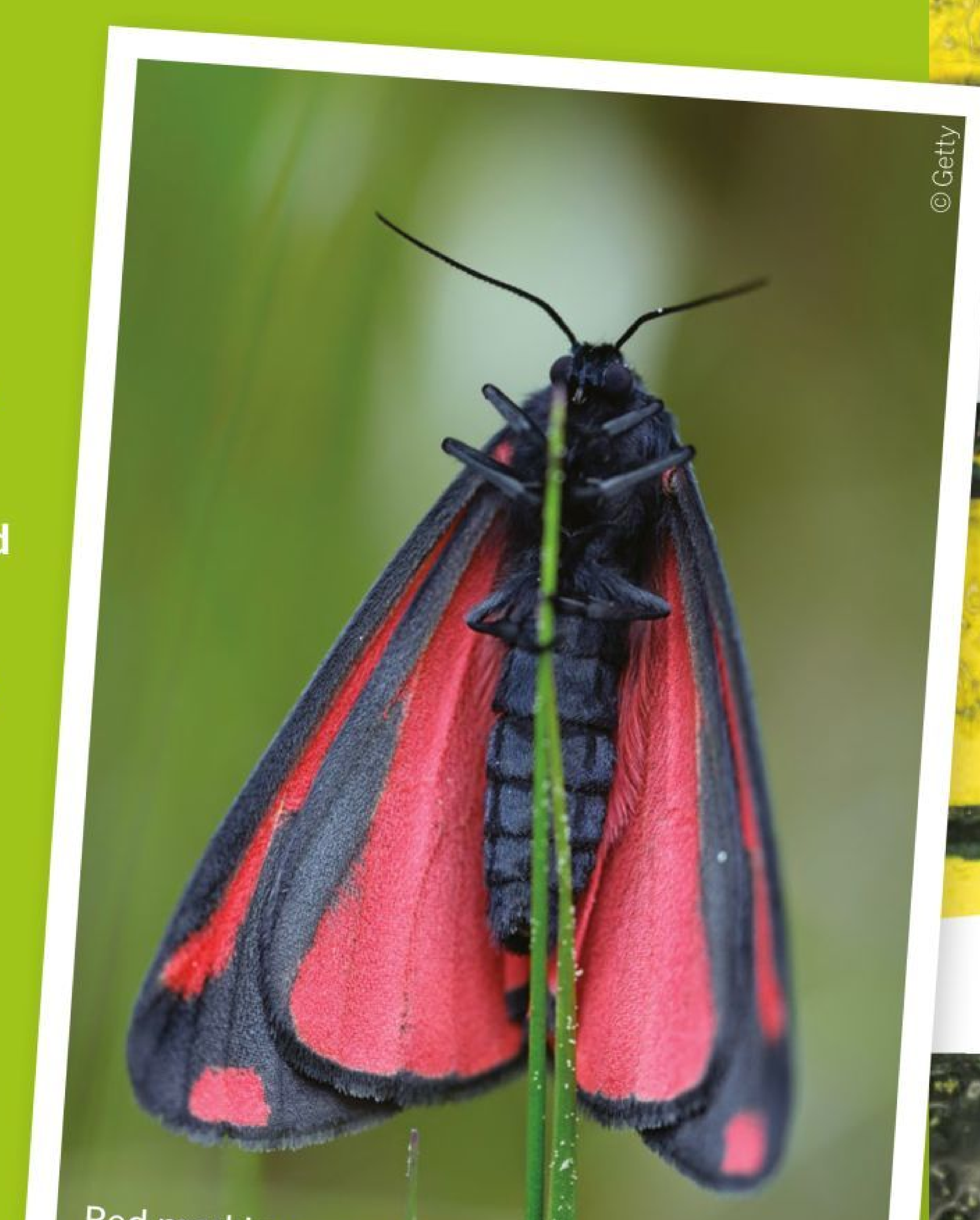
> *"Causing anything from cardiac arrests to blistering skin ulcers, a run-in with the wrong plant can send you to the emergency room"*

Stealing poison power

Immunity to the world's poisonous plants isn't enough for some creatures: some have evolved to take the poison so that they can use it for themselves. Researchers at the Botanical Institute at Christian-Albrechts-Universität zu Kiel (CAU) dedicated ten years to understanding toxic plants and how insects ingest them.

The team found that a collection of insects have evolved the ability to consume toxins called pyrrolizidine alkaloids (PA) within poisonous plants without harm. This is due to an enzyme within their bodies that prevents the PA causing damage to any of the insects' cells. It not only neutralises the poison's effects while ingested in the beetles' haemolymph (an insect version of blood), but the PA is then biologically transported into their defence glands to be secreted when under threat from a predator. These insects literally take the poison out of plants and use it as their own weapon.

Other invertebrates, such as the cinnabar moth, ingest PA and simply store it within their bodies. Paired with a vibrant appearance – nature's warning signs – predators are alerted that these insects are packing poison.

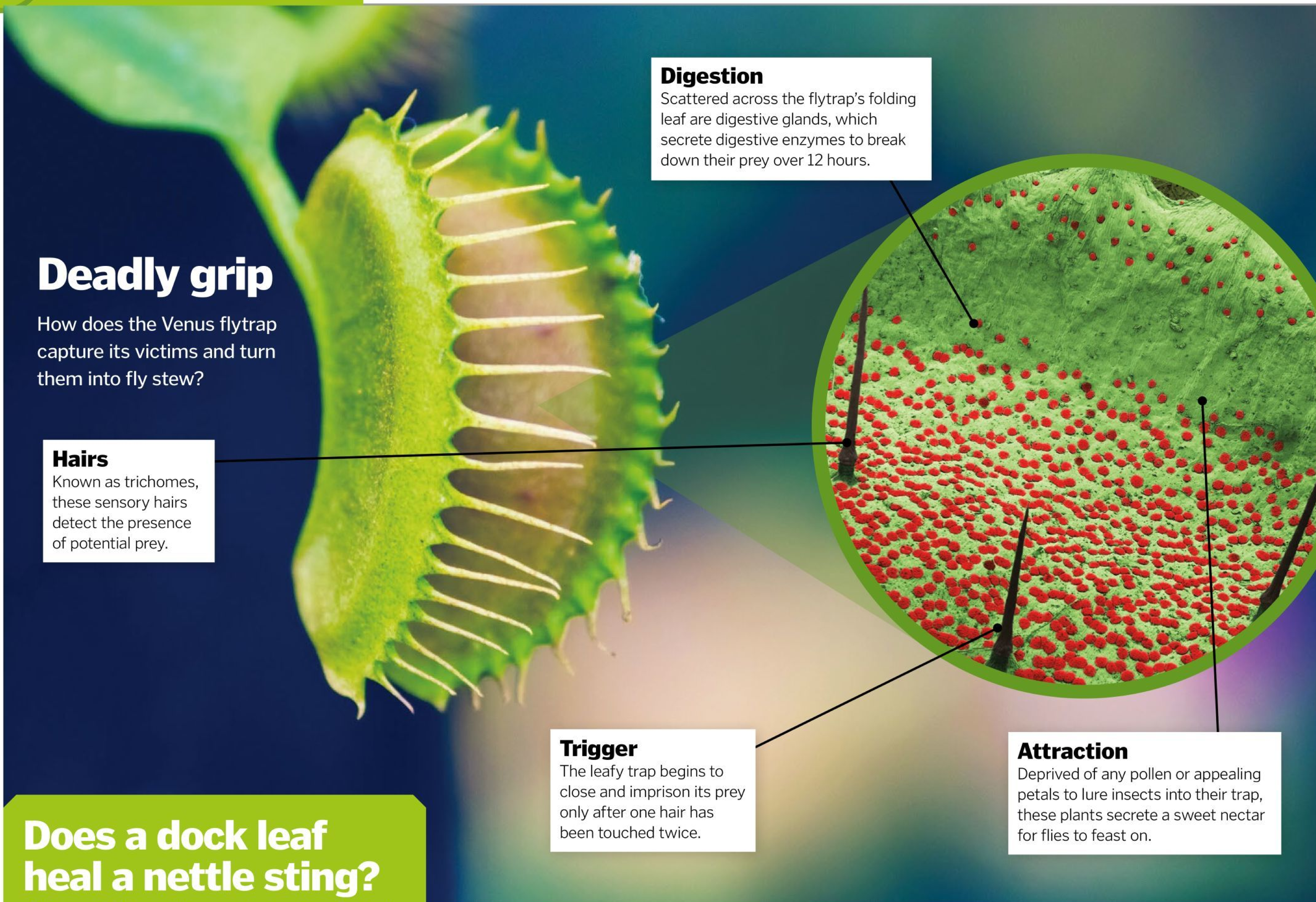


Red markings on the cinnabar moth indicate it will leave a toxic taste behind if eaten

© Getty

Deadly grip

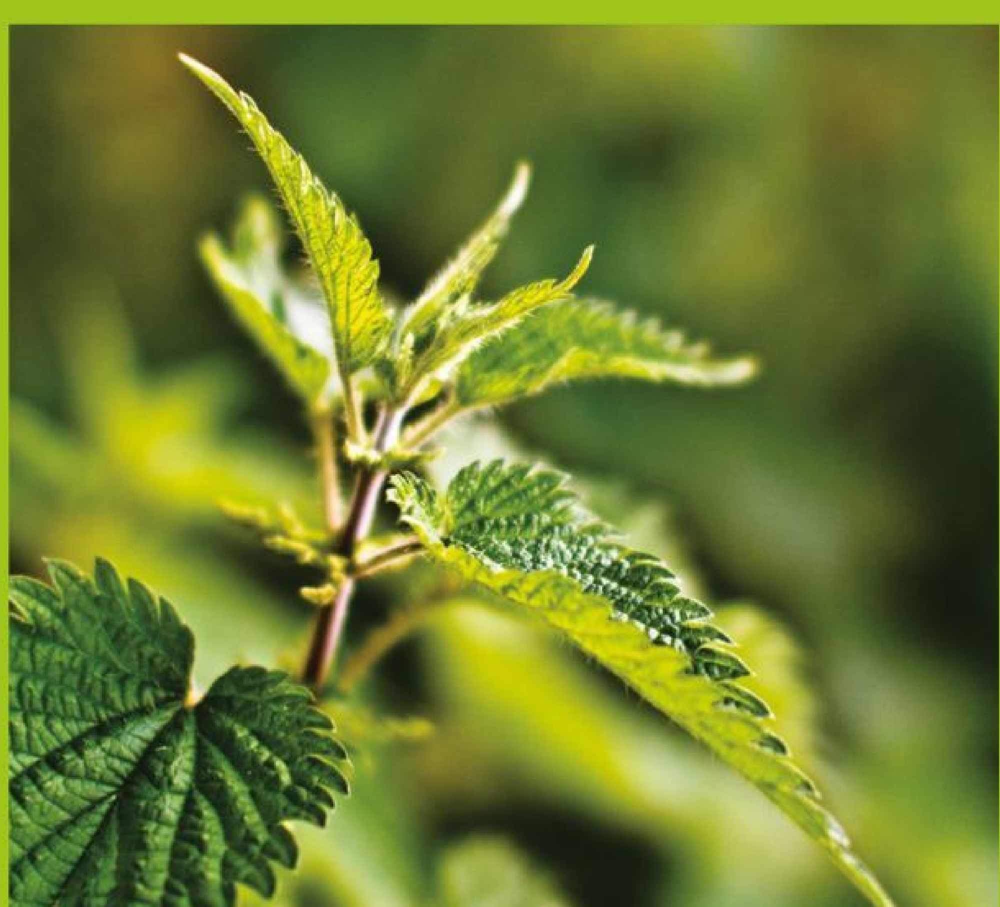
How does the Venus flytrap capture its victims and turn them into fly stew?



Does a dock leaf heal a nettle sting?

Although it's not the most deadly of plant species, a sting from the common nettle can still pack a nasty punch. Coated on each leaf's surface are tiny hollow hairs loaded with a cocktail of irritant formic acid and histamines, which enter the skin when pierced.

To soothe the burning sensation of a nettle sting, rubbing the nearest dock leaf over the wound is often believed to help. Its healing abilities are often attributed to an alkaline sap that neutralises the acidic sting. However, this is simply not the case. It's possible that the evaporation of the broad leaves' moisture on the skin may cool the burning sensation, but its famous healing abilities are a myth.



Formic acid in the nettle's spiny hairs penetrates the skin, causing irritation and discomfort

> *"There is a killer collection of plants that feast on the flesh of passing insects and even amphibians"*

leaves. Although they're toxic to most other species, eucalyptus leaves are detoxified by cytochrome P450 enzymes in the koala's large caecum (digestive pouch). These enzymes break down the toxins rapidly, allowing the animals to consume the leaves without fear of injury. However, due to the low-calorie value of the eucalyptus, koalas have to consume about 400 grams of leaves and sleep for up to 22 hours.

Packing poisons is only one of the many ways plants are some of the most deadly organisms on Earth. Although harmless to human hands, there is a killer collection of plants that feast on the flesh of passing insects and even amphibians. Known as carnivorous plants, Venus flytraps and pitcher plants have evolved to not only take sustenance from traditional methods of photosynthesis but also actively eat passing prey. Typically, these pitcher plants feast on a variety of insects, but a recent study found that one in five pitcher plants in Ontario, Canada's Algonquin Provincial Park have been chowing down on juvenile salamanders. The way these saxophone-shaped plants digest their prey is by luring them into a pool of collected rainwater. Once the salamanders have taken a dip, they cannot climb the pool's waxy walls and find themselves trapped. The pitcher plant then secretes digestive enzymes into the salamander's watery grave.

Having died naturally from either starvation or overheating, the salamanders decompose in about ten days. The pitcher plant will then absorb its nutrients from this 'salamander stew' as a tasty treat.

Having evolved an immunity to toxic leaves, koalas can feast on eucalyptus for hours

The 10 most poisonous plants

Oleander *(Nerium oleander)*

Native: Eurasia and North Africa

Generally considered the worst of the bunch, this plant is poisonous from root to petal. Equipped with the toxin oleandrin, oleander can cause vomiting, irregular heartbeats and even death. Ingesting one leaf is enough to be fatal.

©Getty

Water hemlock *(Cicuta maculata)*

Native: North America

Don't be fooled by this plant's angelic flower: this is one of the world's most poisonous plants. Flowing through every part of the plant is a cicutoxin that can cause convulsions, muscle tremors and death. Toxins are highly concentrated in the roots.

© Choess

Rosary pea *(Abrus precatorius)*

Native: Asia and Australia

Less than three micrograms of the toxin abrin is enough to be fatal, making it deadlier than ricin. Oddly, the toxin is only held in the casing. Once that's broken, the abrin is released, but swallowing the seeds whole is relatively safe.

© Vinayaraj

Deadly nightshade *(Atropa belladonna)*

Native: Eurasia and North Africa

Deadly nightshade has a potent ability to paralyse the body's nerves. It causes injury to the heart and intestinal muscles, and it only takes ingesting ten to 20 berries to be fatal to an adult.

© Donald Macauley

Castor bean *(Ricinus communis)*

Native: East Africa

Although castor oil is safe and used in food and drug production as well as beauty products, the seeds contain the poison ricin. Eating an unprocessed bean can lead to internal bleeding, vomiting and circulation failure.

©Getty

Suicide tree *(Cerbera odollam)*

Native: Asia and Australia

The suicide tree is named for its seemingly harmless yet deadly fruit. Each seed is highly concentrated in a potent cardiac glycoside called cerberin. The seeds of the tree can slow down the heart's rhythm, sometimes to a fatal extent.

© Vengolis

White snakeroot *(Ageratina altissima)*

Native: North America

This plant can cause what is commonly known as milk sickness if ingested by cattle: meat and milk by-products can contain a toxic alcohol, known as trematol, that can lead to vomiting, muscle stiffness and death.

© H. Zell

Aconite *(Aconitum napellus)*

Native: UK

Toxic to the touch, aconite can cause numbness and even heart difficulty after contact thanks to its alkaloid toxins. Often mistaken for horseradish roots, this plant can cause vomiting, high blood pressure and diarrhoea when ingested.

© Léna Gahery

Jimson weed *(Datura stramonium)*

Native: Central America

Jimson weed, also called devil's snare, is a plant in the nightshade family. Ingested in high quantities, its poison can cause seizures or place you in a coma. Its alkaloid toxins have also been known to cause hallucinations.

©Getty

Manchineel tree *(Hippomane mancinella)*

Native: Central America

Few poisonous plants can infect their victims by a simple touch. Laced with a cocktail of poisons, this tree's sap will cause irritation to the skin and eyes. Bite into the apple-like fruit and your mouth will quickly blister.

© Jason Hollinger

The Rainbow Mountain

Discover the origins of the colours cascading over Peru's iridescent Ausangate Mountain

Stretching over 7,200 kilometres along the western spine of South America, the Andes is the world's longest mountain range. It spans seven countries, but it is in Peru where one mountain in particular stands out from its surroundings.

Around 100 kilometres from the Peruvian city of Cusco is Vinicunca Mountain, which looks as though it's from the world of Dr Seuss rather than our own. Stripes of alternating yellows, reds and greens coat every undulation and edge of its rocky protrusions, giving the 'Rainbow Mountain' its nickname.

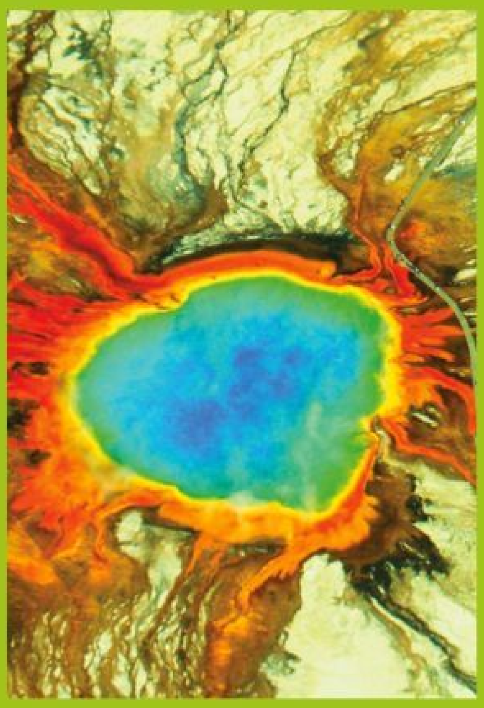
This multicoloured appearance is the result of millions of years of sediment layering. Over time, layers of different sediments with different mineral and chemical compositions (dependent on the environment at the time) covered one another. While exposed to Earth's atmosphere, each layer's composition reacts with the elements in the air, such as oxygen. It's these interactions that produce the array of colours to form the mountain's rainbow appearance. Iron-rich sediment creates the red iron oxide layers, iron sulphide is responsible for the yellow layers and chlorites produce the green.

The Andes formed around 6 to 10 million years ago when the oceanic Nazca Plate subducted (slid underneath) the continental South American Plate, causing uplift. It is thought that this tectonic interaction also generated a lot of volcanic activity, which could explain the presence of the mountain's multicoloured minerals. Through millennia of further tectonic activity these sediment layers have been tilted on their side, so the stripes appear to run vertically.

Thousands of years of weathering has helped create the mountain's rusty shades

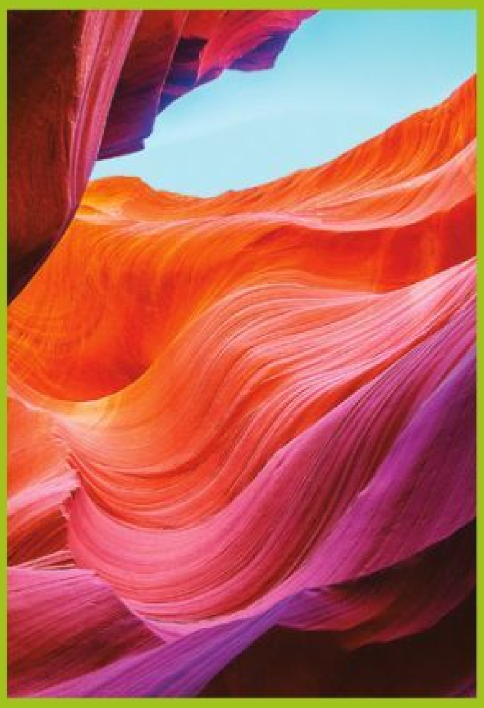
Earth's vibrant formations

Alum Bay, UK
These clifftops are comprised of quartz, feldspar and mica, but due to contamination from other minerals the cliffs display a mottled array of reds, greens, yellows and browns.

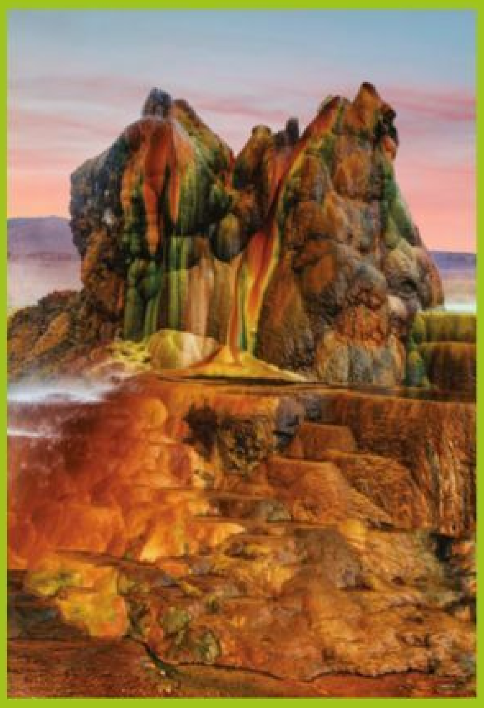


The Grand Prismatic Spring, Wyoming, US
Found in Yellowstone Park, this spring hosts several species of bacteria, which contribute to its rainbow graduation.

Zhangye Danxia, China
Known as the 'The Rainbow Mountains of China', these colourful creations of the Himalayas formed by a similar method to their Peruvian counterparts.



Antelope Canyon, Arizona, US
One of the most photographed places on Earth, this canyon's flowing sandstone appears to change colour depending on sunlight, depth and the weather.



Fly Geyser, Nevada, US
This semi-artificial formation was a failed attempt at drilling a well; the geyser created its colourful cone structure as algae and minerals in the water collected on the surface.

How coral reefs form

Corals are team players, collaborating to build the largest living structures on Earth

Covering just 0.1 per cent of the world's surface, coral reefs are home to around 25 per cent of all the species in the ocean. These seemingly static structures are constantly surrounded by colour and movement, and while they're often mistaken for rocks or plants, the corals themselves are living animals; they belong to the group Cnidaria, along with jellyfish and sea anemones.

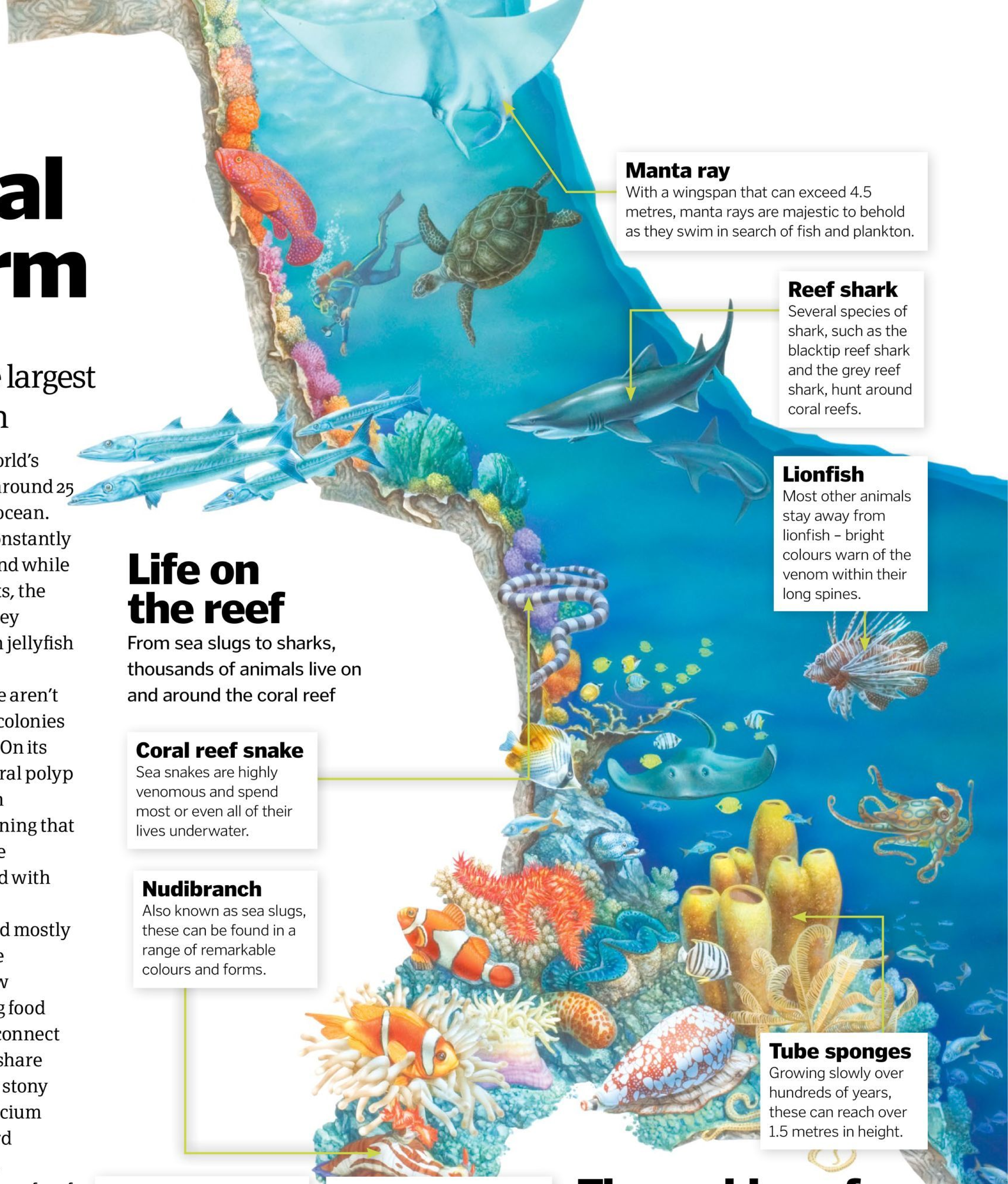
Corals can grow to vast sizes, but these aren't enormous individual animals – they're colonies made up of thousands of tiny creatures. On its own, each invertebrate is known as a coral polyp and can be as small as one centimetre in diameter. These polyps are sessile, meaning that they remain in a single spot once they've reached maturity and catch passing food with tentacles around their mouths.

The structure of a coral reef is provided mostly by the stony corals, or hard corals. These reef-building corals grow best in shallow tropical water with fast currents to bring food their way. Polyps slowly aggregate and connect their gastrovascular canals so they can share nutrients. Hard coral colonies gain their stony appearance through the secretion of calcium carbonate, a compound that forms a hard exoskeleton around the delicate polyps.

The hard skeletons and twisting shapes of reef corals provide shelter for a variety of creatures. Animals like shrimps and crabs defend homes made in the nooks between branches, and many species spawn around the reef to protect their young from the strong current. Single-celled algae called zooxanthellae even share the energy they produce from photosynthesis in exchange for lodgings within a polyp's body.

Life on the reef

From sea slugs to sharks, thousands of animals live on and around the coral reef



Manta ray
With a wingspan that can exceed 4.5 metres, manta rays are majestic to behold as they swim in search of fish and plankton.

Reef shark
Several species of shark, such as the blacktip reef shark and the grey reef shark, hunt around coral reefs.

Lionfish
Most other animals stay away from lionfish – bright colours warn of the venom within their long spines.

Coral reef snake
Sea snakes are highly venomous and spend most or even all of their lives underwater.

Nudibranch
Also known as sea slugs, these can be found in a range of remarkable colours and forms.

Tube sponges
Growing slowly over hundreds of years, these can reach over 1.5 metres in height.

The making of a coral colony

Fringing reef
Free-swimming coral larvae settle and attach themselves to submerged rocks.

Barrier reef
Fringing reefs around an island can join up to form a border around the whole coastline.

Atoll
If a volcanic island subsides below the waves, it leaves behind a coral atoll.

The Great Barrier Reef is considered one of the wonders of the natural world

The Great Barrier Reef

Comprised of over 2,500 individual reef systems and hundreds of tropical islands, Australia's Great Barrier Reef is the most extensive reef ecosystem on the planet. It covers almost 350,000 square kilometres; it's so large, in fact, that it can be seen from space.

It has incredible biodiversity. 1,500 species of fish, 4,000 species of mollusc and some 240 species of bird call the reef home. Anemones and sponges add colour, while crustaceans and marine worms fill the reef with movement. Threatened species like the green turtle and dugong can still be found here, and clouds of butterflies head to the islands for the winter.

The Great Barrier Reef is a haven for wildlife. Most of the ecosystem's area has been a World Heritage Site since 1981, but its future is far from certain. Pollution, climate change, unsustainable fishing and coastal development all threaten this iconic reef.

ANIMAL ANTIDOTES

How do some creatures survive being bitten and stung by the most venomous nasties on Earth?

Words by **Scott Dutfield**

Whether it's the bite from a viper, a sting from a scorpion or the subtle swipe of a jellyfish, the world's venomous species have evolved the ability to deliver a killer cocktail of chemicals. However, there are those who have also evolved immunity to their effects.

There are roughly three types of venom among the more notorious of the 600 venomous species of snake. Neurotoxins affect the body's nervous system, blocking communications between nerves and ultimately shutting it down altogether, resulting in paralysis. The second, hemotoxins, bring about a particularly gruesome demise. These toxins attack the body's red blood cells, making them coagulate to form gelatinous blood clots. Finally, cytotoxins are those that begin to digest the body's cells before the snake has even swallowed its prey.

As predators and as prey, venomous snakes are formidable opponents, but certain species are able to tackle them head-on without fear. The mongoose is the deadly cobra's worst nightmare. In order for this snake's neurotoxic venom to work the toxin must be able to bind with receptors on nerve cells. However, the mongoose's nerve receptors have mutated in a way that prevents this kind of binding, thus


Mongooses have evolved to resist the deadly venom of the cobra

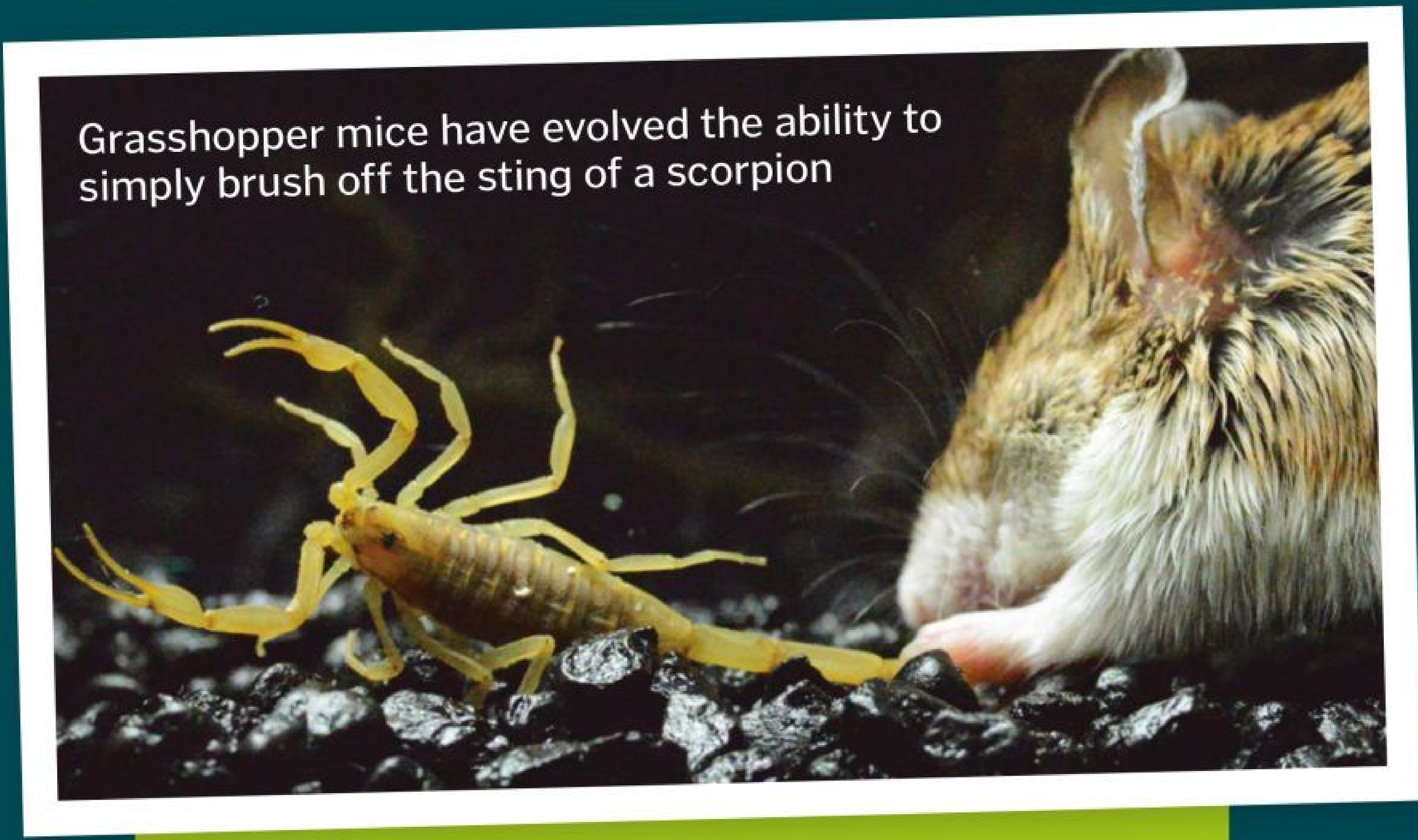
Secretary birds use a force equivalent to five times their own body weight to strike their prey

Kung-fu birds

Snakes not only have to fear the threat of attack from land but also the skies. Winged kung-fu killers, secretary birds have developed a martial arts method to feast on snake flesh. While not strictly anti-venom – they do not possess an internal immunity to tackle snake venom – these birds avoid bites by delivering several rapid-fire blows to a snake's skull.

One study found that on average it took just 15 milliseconds for the bird to strike the snake's head. Delivering a 20-kilogram-force blow to the head, secretary birds are able to disarm a venomous snake without feeling the force of their bite.

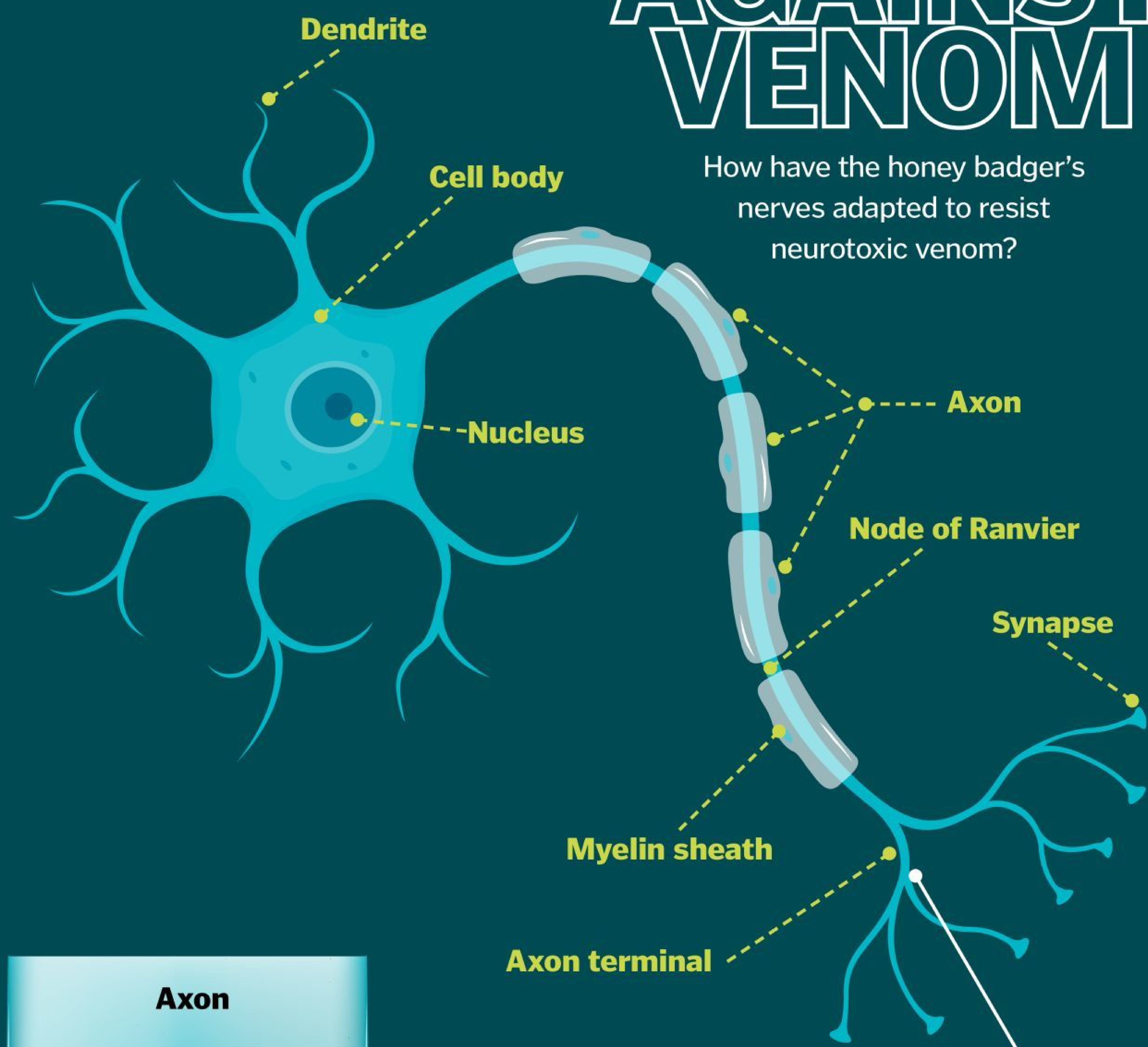
Mongooses typically eat small animals such as snakes, birds and fish



Grasshopper mice have evolved the ability to simply brush off the sting of a scorpion

DEFENCE AGAINST VENOM

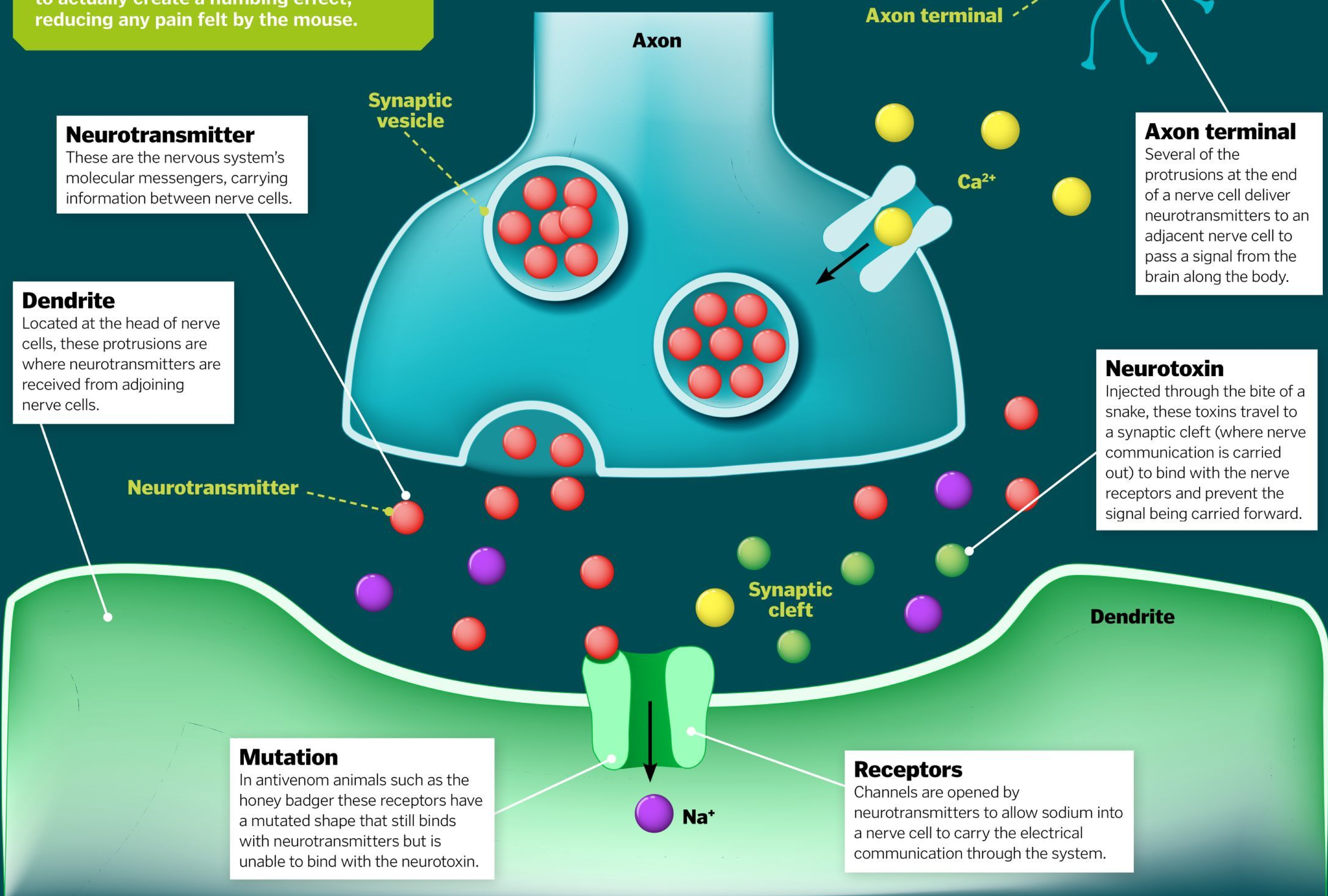
How have the honey badger's nerves adapted to resist neurotoxic venom?



Rodent resistance

The sting of a scorpion can be fatal to many rodents who come in close contact with them. There is one, however, that has baffled researchers for not only its ability to prey on these sting-equipped insects, but to do so unscathed.

Native to the southwestern United States, the grasshopper mouse has taken a liking to the taste of bark scorpion. Deadly to other animals, when stung the desert-dwelling grasshopper mouse simply licks its paws and finishes its meal. It's still unclear exactly how the mouse is immune to the scorpion's sting, though it is thought to be related to a protein released at ion channels on the rodents' nerve cells. By binding with the injected toxin, these proteins are thought to actually create a numbing effect, reducing any pain felt by the mouse.



Neurotransmitter
These are the nervous system's molecular messengers, carrying information between nerve cells.

Dendrite
Located at the head of nerve cells, these protrusions are where neurotransmitters are received from adjoining nerve cells.

Axon terminal
Several of the protrusions at the end of a nerve cell deliver neurotransmitters to an adjacent nerve cell to pass a signal from the brain along the body.

Neurotoxin
Injected through the bite of a snake, these toxins travel to a synaptic cleft (where nerve communication is carried out) to bind with the nerve receptors and prevent the signal being carried forward.

Mutation
In antivenom animals such as the honey badger these receptors have a mutated shape that still binds with neurotransmitters but is unable to bind with the neurotoxin.

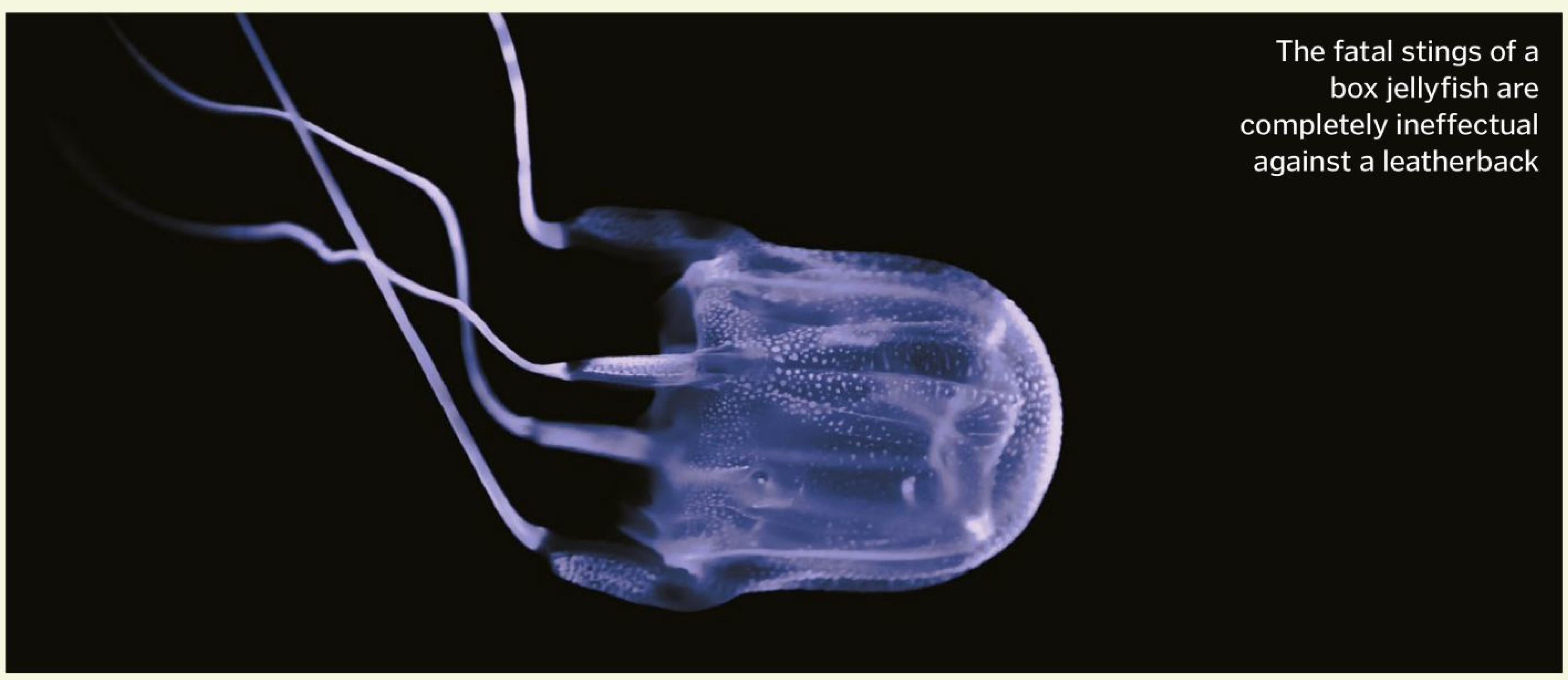
Receptors
Channels are opened by neurotransmitters to allow sodium into a nerve cell to carry the electrical communication through the system.

immunising it to their paralysing effects. The mongoose is not alone in its fight against the forces of neurotoxins: honey badgers, ground squirrels and even hedgehogs are among some of the mammals able to endure an otherwise fatal dose of neurotoxin from the fangs of a snake.

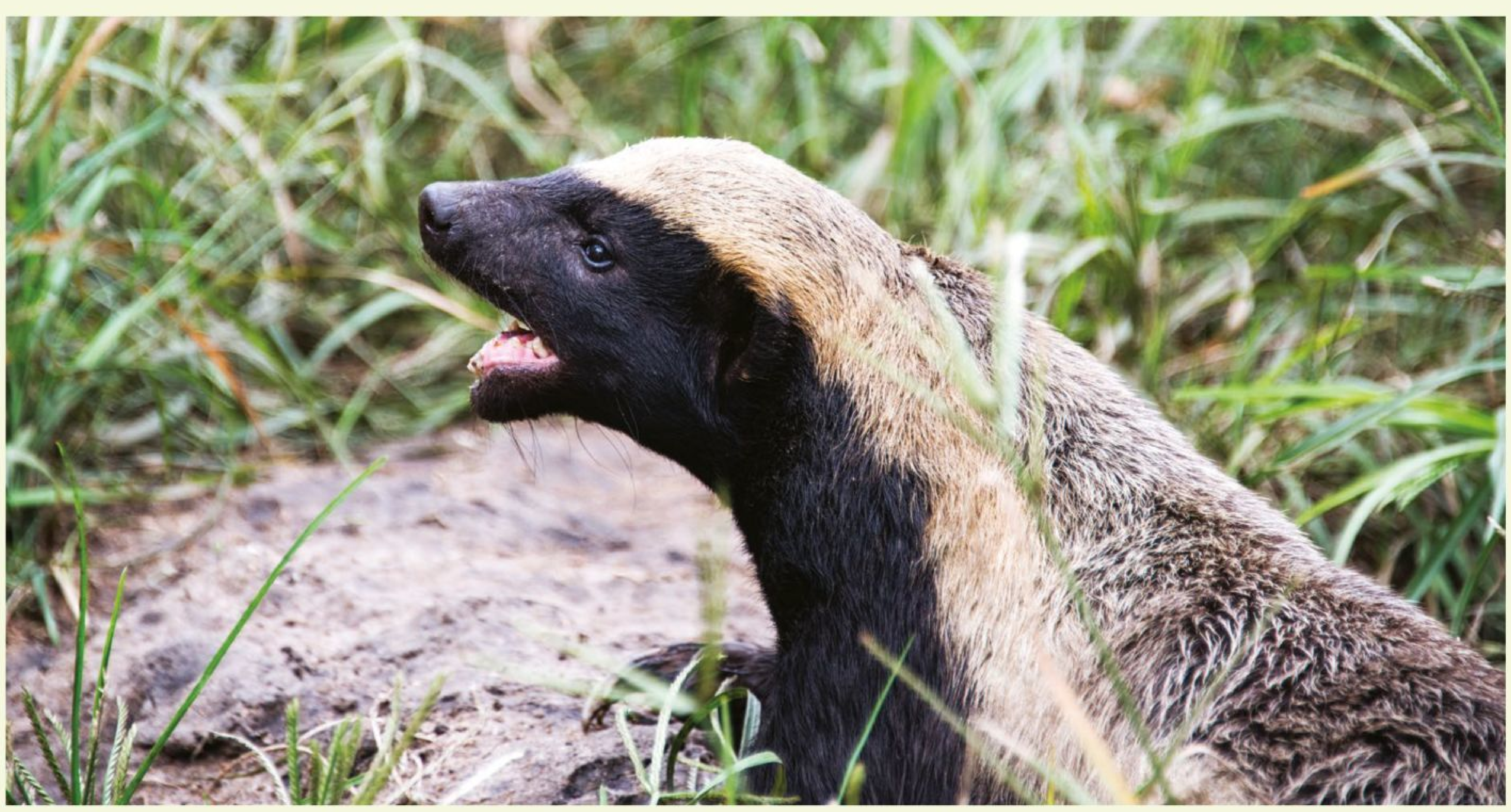
The North American opossum is also well-equipped for a battle in the bloodstream, with the ability to neutralise the venom of around 12 species of venomous snakes. The western diamondback rattlesnake, for example, is one such species. This snake's particular brand of toxin is a hemotoxic venom, which infiltrates the bloodstreams of their prey or aggressor, hijacks its blood cells and destroys their internal organs and circulatory system. The opossum, however, has a blood cell bodyguard in the form of a chain of amino acids in its blood that are able to neutralise invading venom.

Arguably the world's most venomous species, the box jellyfish is able to disable and kill many living creatures in seconds. With each tentacle equipped with 5,000 stinging cells, these formidable creatures don't seem like potential food, yet leatherback turtles feast on jellyfish almost exclusively. Unlike the other mammal antivenom members, leatherback turtles have a physical adaptation to defend against one of the world's most venomous jellyfish. Lining its thick oesophagus that leads towards its stomach are continuous rows of inward-facing papillae, or protrusions. Made from hard keratin, the same material found in fingernails, the sting of a jellyfish is rendered useless by them.

Built-in blood bodyguards prevent an opossum's blood from being affected by venom



The fatal stings of a box jellyfish are completely ineffectual against a leatherback



Honey badgers have evolved an immunity to the neurotoxic venom of snakes

Q&A

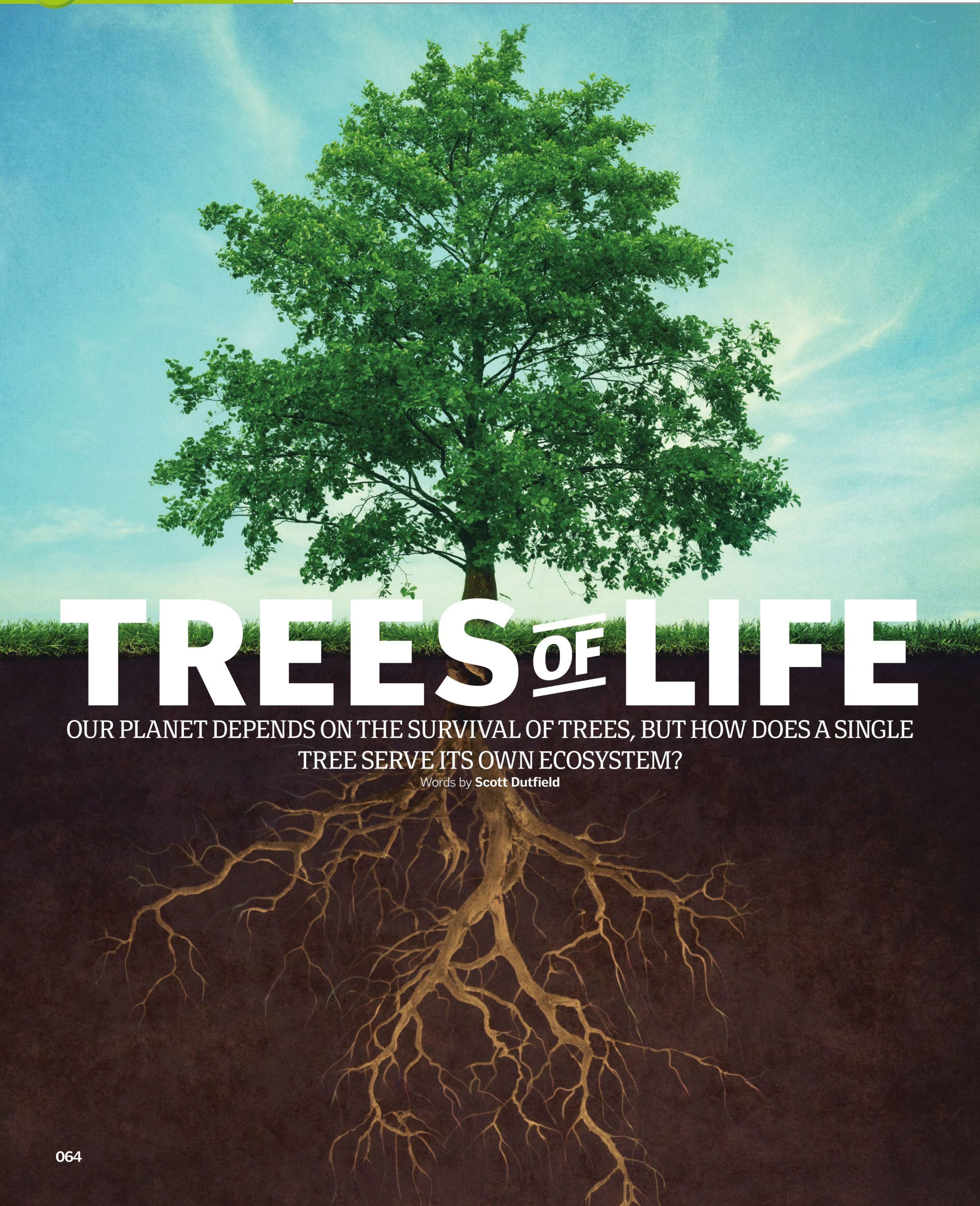
Q&A with venom expert Bryan Fry

An associate professor at the school of Biological Sciences, University of Queensland, as a biochemist and molecular biologist Bryan has spent his career expanding our understanding of venom and its evolution.

How have venomous snakes evolved immunity to their own venom?
This has been accomplished through a myriad of mechanisms ranging from structural modifications of neurological receptors through to circulating factors that neutralise toxins.

Can the venom of snakes from the same or different species affect one another?
They will be immune to venom from snakes that have similar venoms, like those within the same species or from related species. However, some species have venom that varies dramatically across the range, and therefore the immunological cross-reactivity would be much less. Such as the Southern Pacific rattlesnake in California, where some populations are neurotoxic and others coagulotoxic [blood-clotting toxins]. Similarly, some species have venoms that change as they age, reflective of young snakes specialising on different prey to adults. Again the degree of immunological cross-reactivity would be affected by this. For example, Australian brown snakes are neurotoxic and specialise on lizards as young snakes but are coagulotoxic and specialise on mammals as adults.

How can our understanding of animal venom immunity help produce antivenom treatments in humans?
It can help us understand the evolutionary patterns for venom diversification, which in turn gives us a better prediction of potential clinical effects and antivenom problems.



TREES OF LIFE

OUR PLANET DEPENDS ON THE SURVIVAL OF TREES, BUT HOW DOES A SINGLE TREE SERVE ITS OWN ECOSYSTEM?

Words by **Scott Dutfield**

Reaching across millions of kilometres, the world's forests are the heart and soul of our global ecosystem. Trees are the yin to mankind's yang; they absorb the carbon dioxide we exhale, and in return they release the precious oxygen our bodies depend on, creating an atmospheric balance. During a tree's lifetime, it will absorb a ton of carbon dioxide, producing around 118 kilograms of oxygen a year in return.

While collectively acting as Earth's air purifier, each individual tree exists in its own micro-ecosystem. From seedling to skyscraper, trees are often at the centre of these ecosystems, supporting the demands for food, shelter and protection from other species. For example, a single tree growing in a tropical rainforest can support around 2,000 different species from across the animal kingdom as well as plant and fungi species.

Fundamentally the role of trees in a micro-ecosystem is to transfer energy in a biological chain, from sunlight to seed production and beyond. Through photosynthesis, trees utilise the energy of the Sun's light to transform absorbed carbon dioxide and water into glucose and oxygen. Stored as chemical energy in glucose, a tree will use this to grow its leafy body and produce its fruits. This chemical energy is then transferred once more to the surrounding animals and insects via a free buffet of fruits, leaves, pollen and nuts. In turn, these creatures will use this obtained energy to survive and even benefit the tree by dispersing its seeds.

> "Each individual tree exists in its own micro-ecosystem"

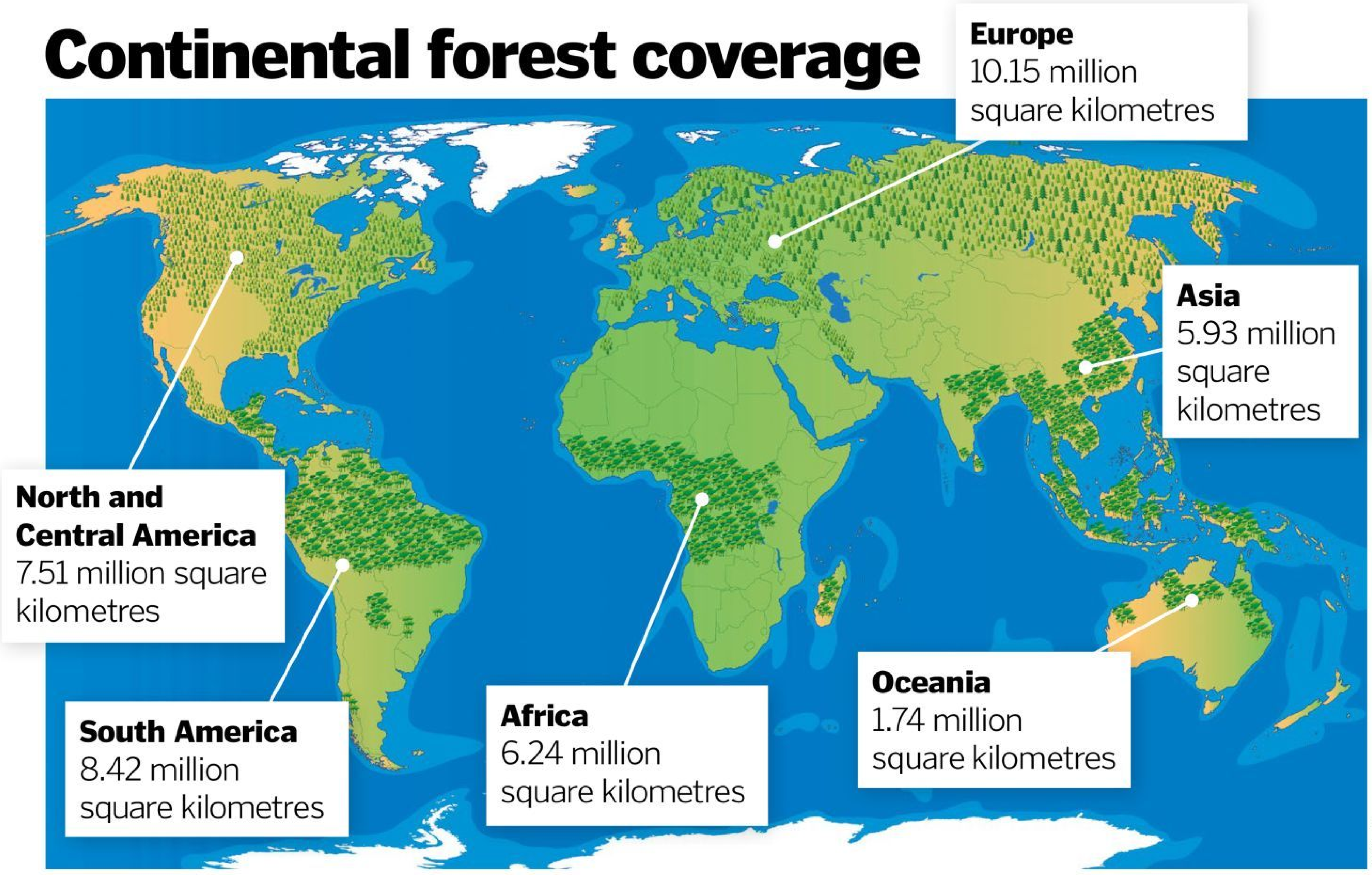
This gifting of energy is not the only way in which trees serve members of a biological community. Non-living 'abiotic' parts of an ecosystem are also kept in check by the presence of trees. Both a tree and the soil it is rooted in mutually benefit from the other's existence. Soil acts as a tree's resource bank of water, minerals and nutrients to be withdrawn by its roots, while fallen leaves and branches restore nutrients to the ground as they decompose. The complex network of roots not only anchor the tree but compact the soil to save it from erosion by rainfall.

The biological and chemical interactions surrounding a single tree are intertwined and affected by the rest of the forest ecosystem and our global ecosystem. A disturbance to smaller ecosystems can have a domino effect on larger ones. For example, during the process of deforestation, each biological community supported by a single tree is also removed. In turn, this can have a negative effect on the diversity of species and the fertility of the land.

© Getty

Gumivores such as the pygmy marmoset feast on the oozing sap of a tree

Continental forest coverage



Gall wasp larvae release a chemical to create their own homes on a tree

© Alamy

The acorn and the wasp

Creating a habitat for animals and insects is a significant role of an oak tree, even when it's tricked into doing so. Found across the leaves, bark and even acorns of many oak trees are small plant pimples called galls. Although they appear as part of the tree's natural knobbly development, galls are in fact the result of a particular group of wasps forcing the tree to build them their very own safe haven. Upon laying its eggs in the tree, an adult gall wasp will leave its larvae to secrete saliva that affects the tree's growth process. In response, the oak tree produces these strange growths, which encase the larvae within. Once engulfed in their temporary wooden shield, the wasp larvae pupate and later emerge as adult wasps.

© Getty

Many mammal species, such as the pine marten, make use of tree hollows to form their own home

© Getty

Lichen can act as a biological indicator of the health of an ecosystem because it absorbs pollution

© Getty

THE MIGHTY OAK

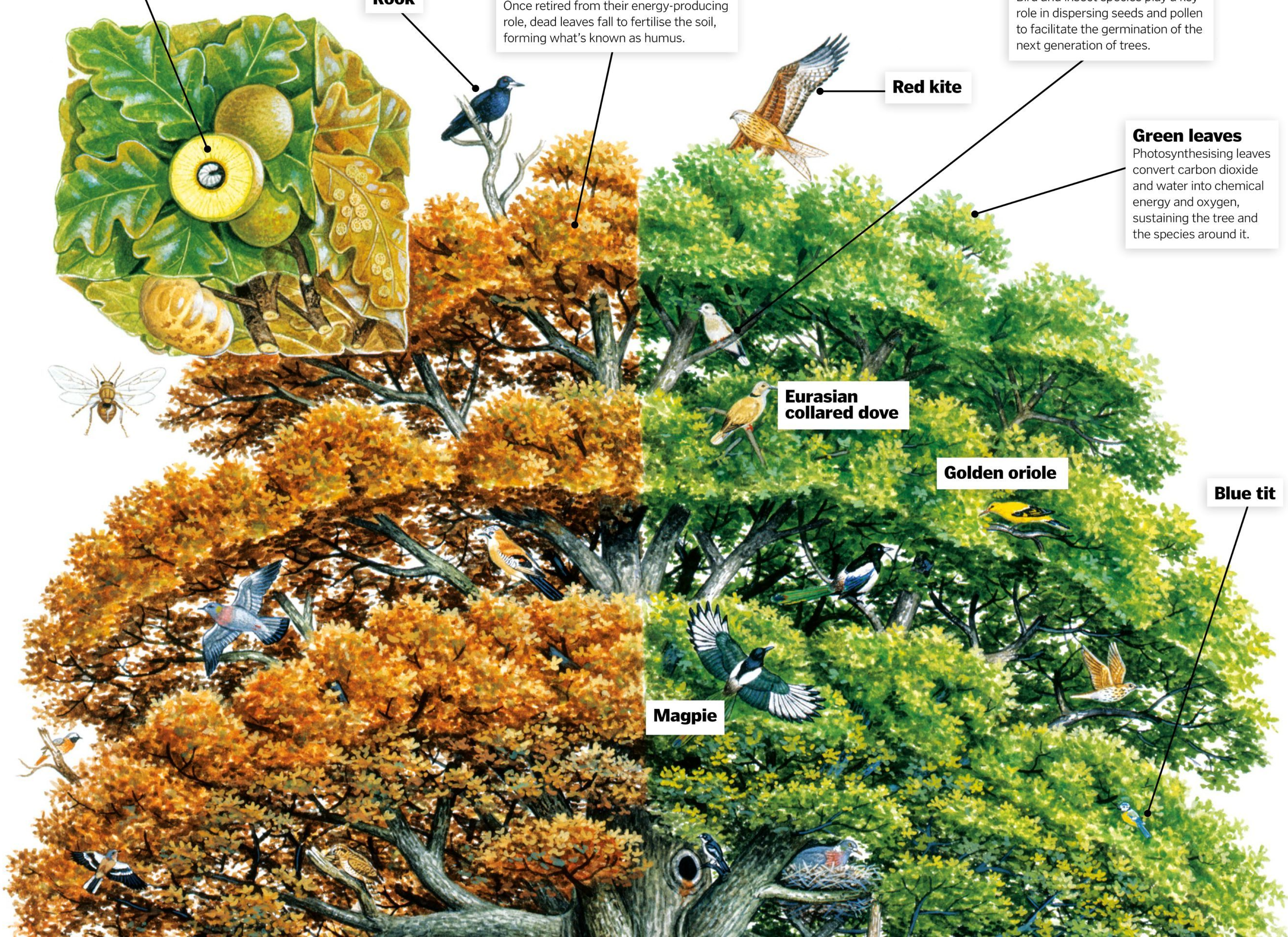
A single oak is brimming with biodiversity throughout the year

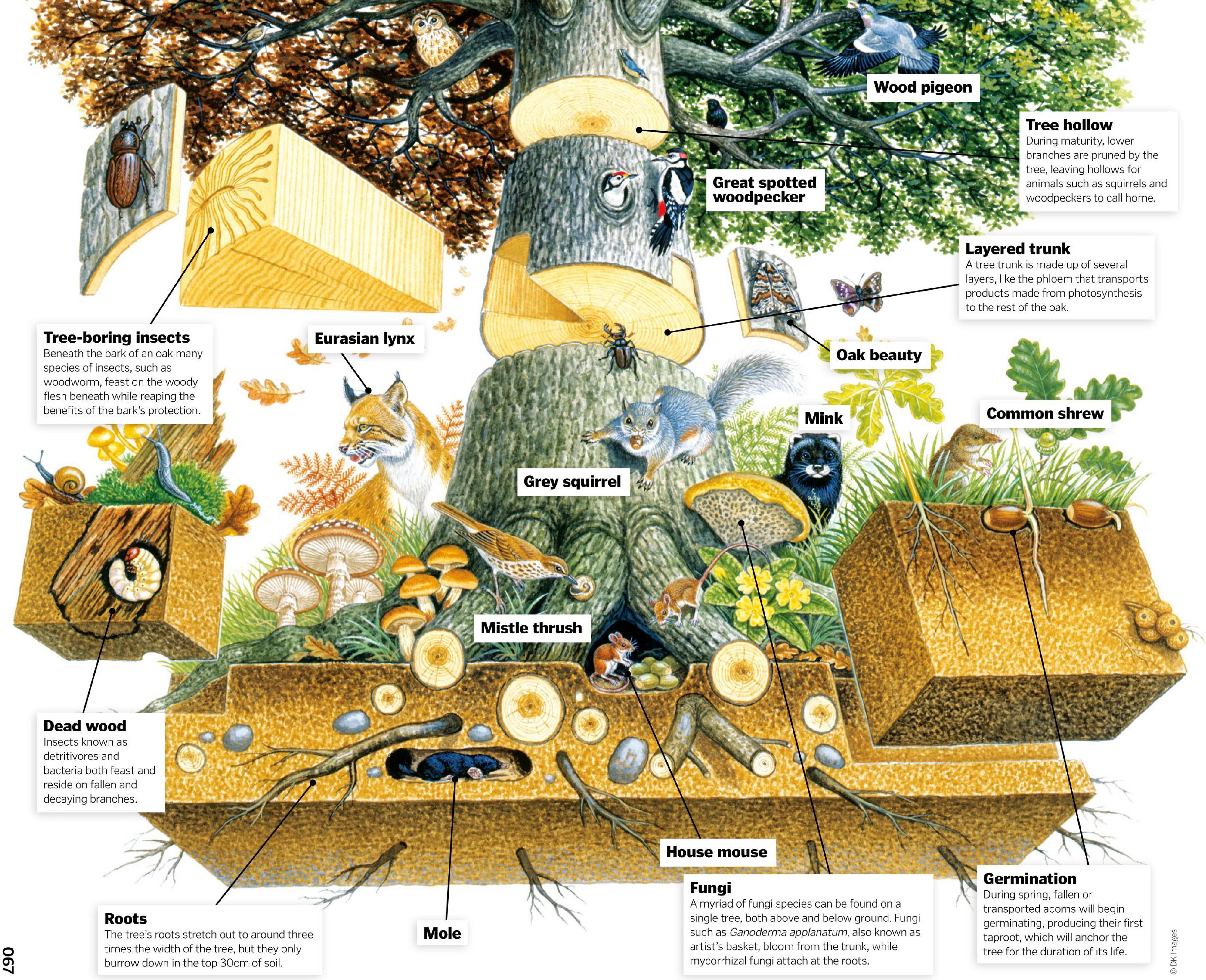
Seeds
Each acorn on an oak tree holds a single seed and will only be produced when a tree reaches the age of around 40 years old.

Autumn leaves
Once retired from their energy-producing role, dead leaves fall to fertilise the soil, forming what's known as humus.

Dispersal
Bird and insect species play a key role in dispersing seeds and pollen to facilitate the germination of the next generation of trees.

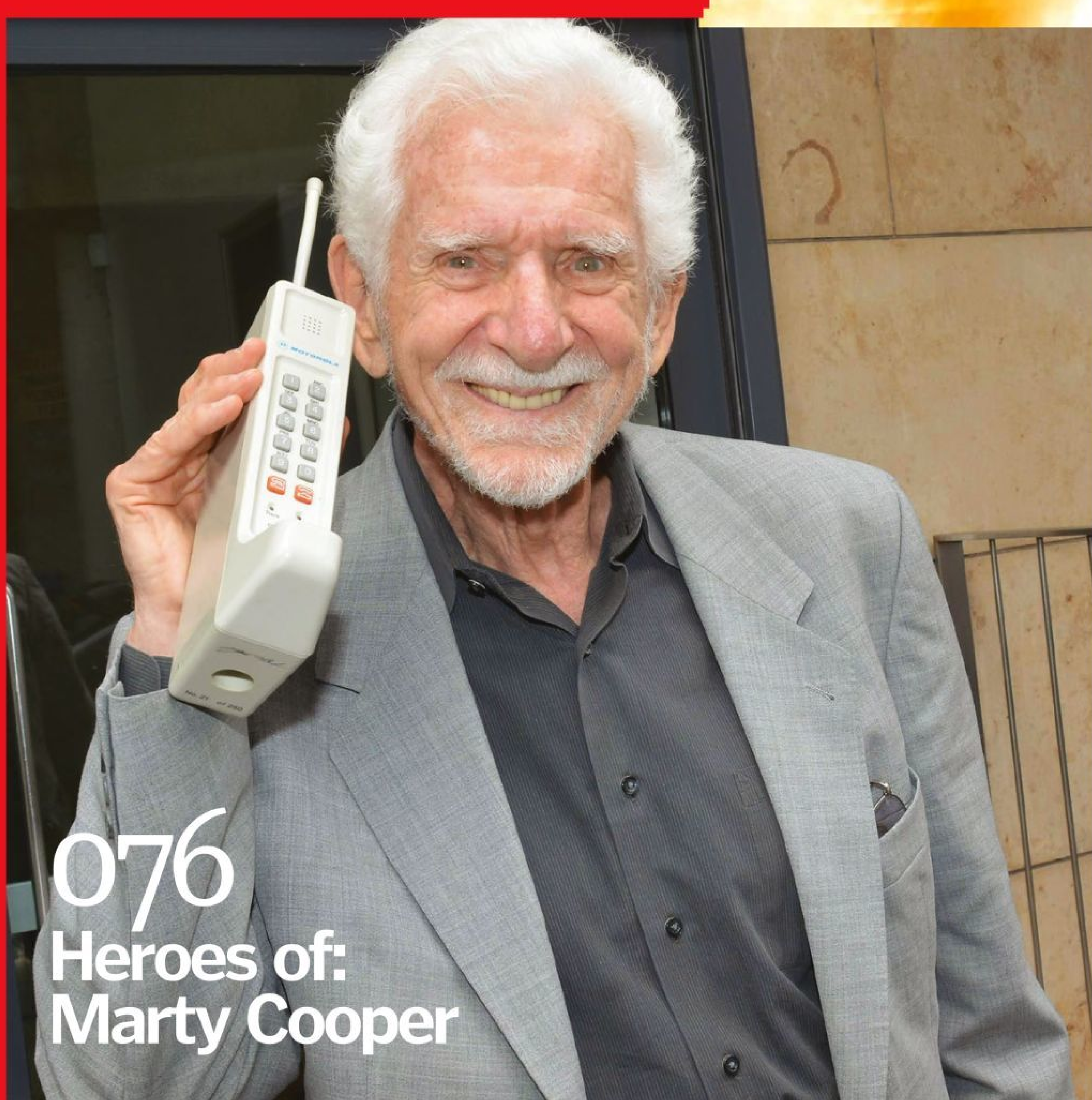
Green leaves
Photosynthesising leaves convert carbon dioxide and water into chemical energy and oxygen, sustaining the tree and the species around it.




Wood pigeon
Tree hollow
During maturity, lower branches are pruned by the tree, leaving hollows for animals such as squirrels and woodpeckers to call home.
Great spotted woodpecker
Layered trunk
A tree trunk is made up of several layers, like the phloem that transports products made from photosynthesis to the rest of the oak.
Oak beauty
Tree-boring insects
Beneath the bark of an oak many species of insects, such as woodworm, feast on the woody flesh beneath while reaping the benefits of the bark's protection.
Eurasian lynx
Mink
Common shrew
Grey squirrel
Mistle thrush
Dead wood
Insects known as detritivores and bacteria both feast and reside on fallen and decaying branches.
House mouse
Roots
The tree's roots stretch out to around three times the width of the tree, but they only burrow down in the top 30cm of soil.
Mole
Fungi
A myriad of fungi species can be found on a single tree, both above and below ground. Fungi such as *Ganoderma applanatum*, also known as artist's basket, bloom from the trunk, while mycorrhizal fungi attach at the roots.
Germination
During spring, fallen or transported acorns will begin germinating, producing their first taproot, which will anchor the tree for the duration of its life.

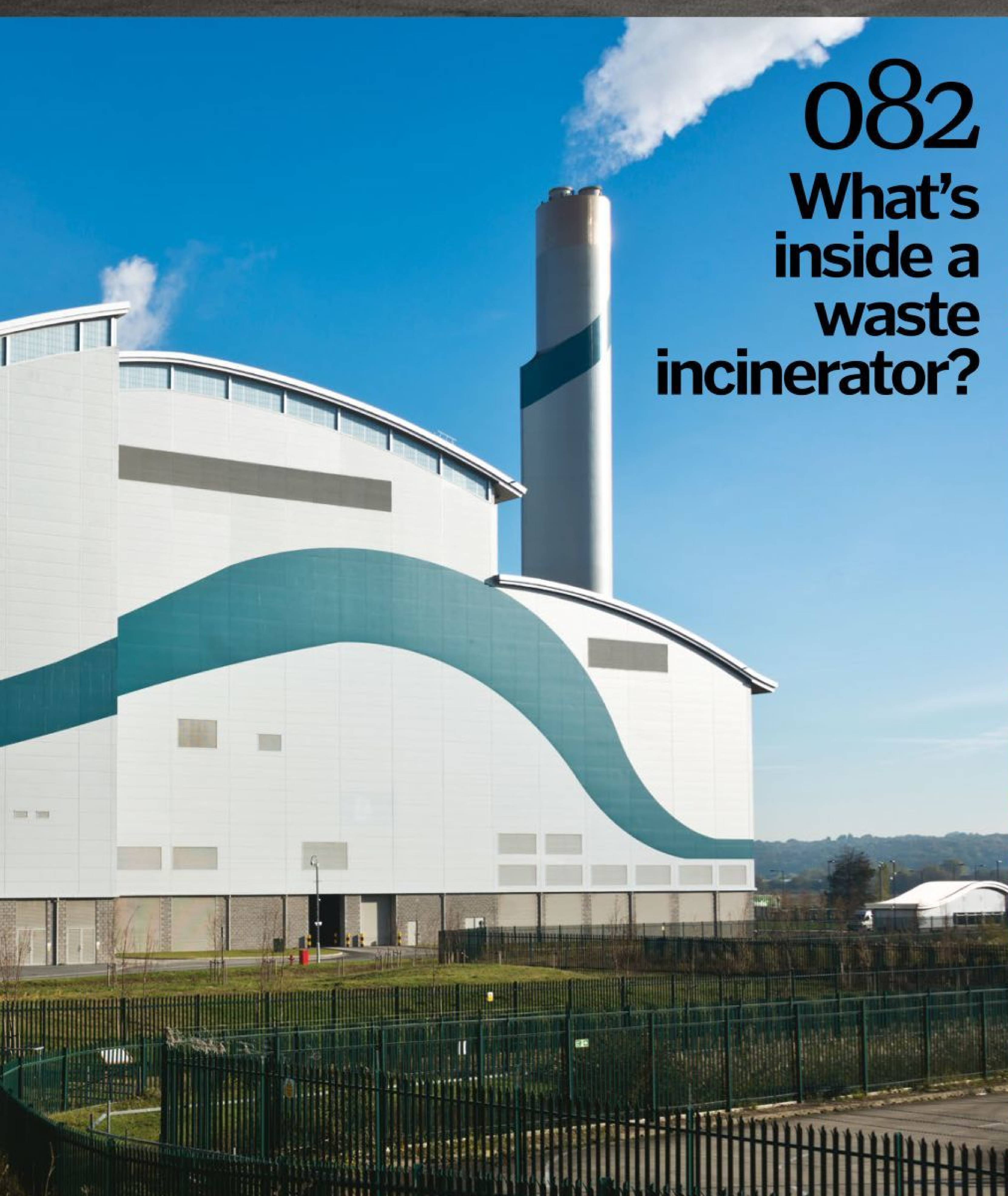
TECHNOLOGY

070
Creating movie magic



076
Heroes of:
Marty Cooper

078
The Thames
Tideway Tunnel



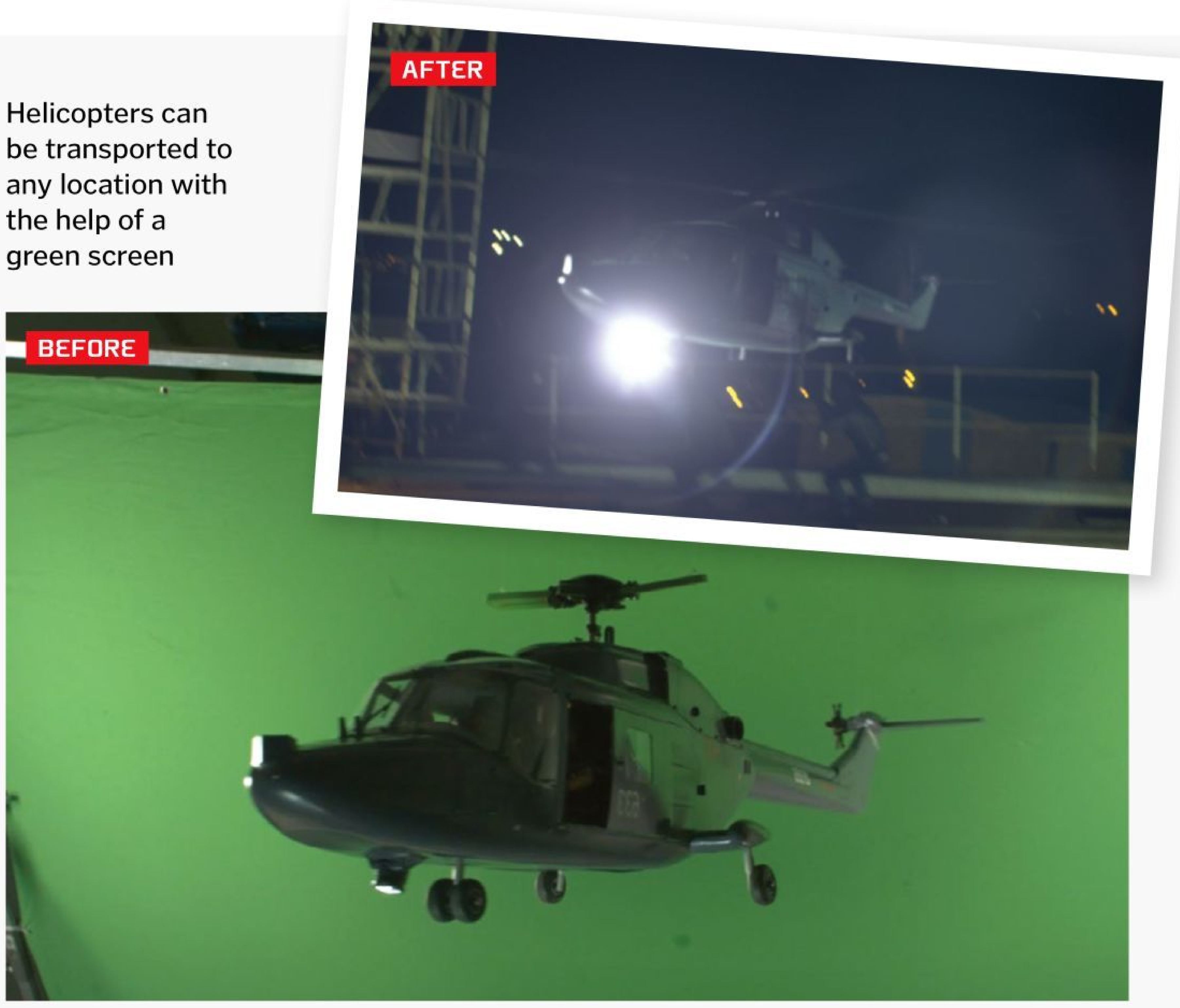
CREATING MOVIE MAGIC

Discover how the cinema is brought to life with computer-generated visual effects

Words by **Scott Dutfield**

Whether it's an explosion behind James Bond, the spellbinding sparks of Doctor Strange or Will Smith's genie makeover in *Aladdin*, visual effects play a vital role in conjuring movie magic. Ditching the days of rubber-faced monsters and visible strings, today's cinema is bursting with the best that visual effects has to offer.

There are two ways in which movie magic can be cast upon a film – as either a special or visual effect. Special effects are typically those achieved on the physical movie set, such as explosions and animatronics, whereas visual effects (VFX) are applied with computer programs after filming a scene, in the post-production stage. Using key techniques, VFX can range from simply changing the light to reflect the time of day to bringing to life a fantastical world drawn from an artist's imagination.



Helicopters can be transported to any location with the help of a green screen

Behind the green screen

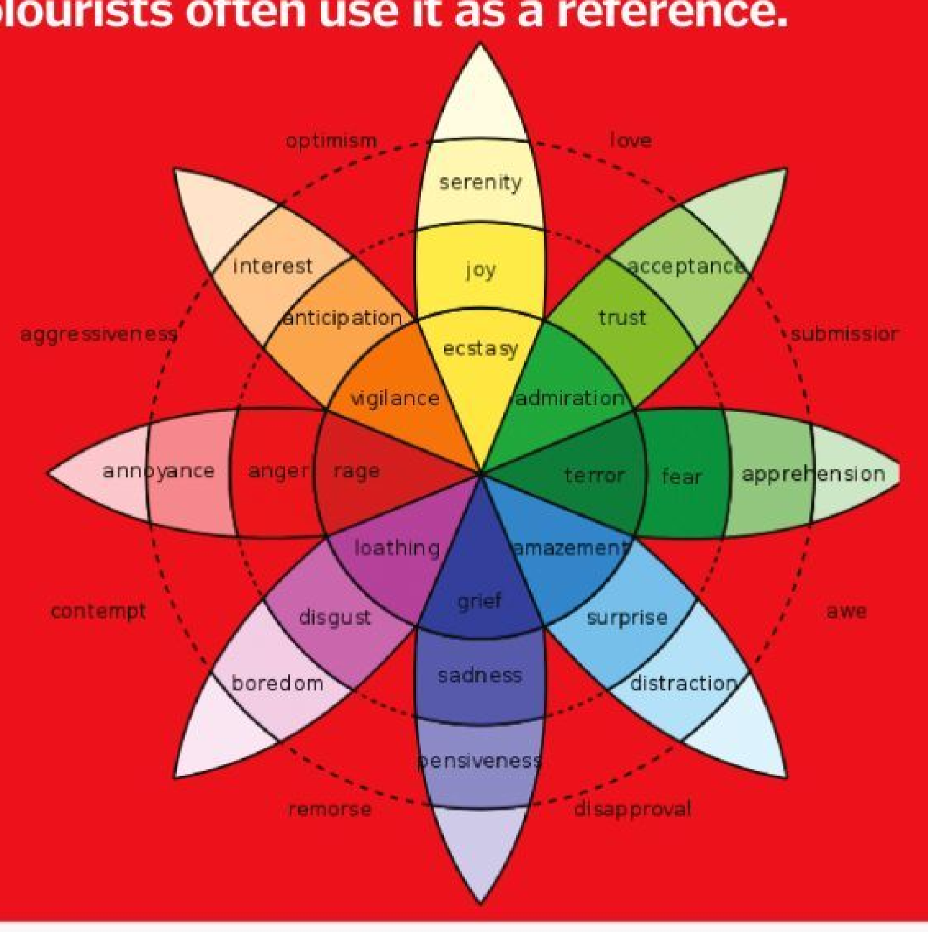
The green screen is an iconic part of visual effects in movies and is also used in TV weather forecasts. Adding VFX via this method is known as 'keying', where artists replace sections of footage with different footage or computer-generated models, for example.

This is achieved by telling design software to remove a certain colour from footage, typically green or blue (depending on the screen colour) and replacing it with VFX elements. Actors in the scene can't wear that colour or their clothes and bodies would vanish into the background. Keying is used to digitally create surroundings that may be too dangerous or unobtainable in real life, or have simply been plucked from an artist's imagination.

'Feeling' colours

Numerous VFX artists and creators will work on a single feature film or TV show. One artistic arm of the production body is the colourists. Tasked with maintaining colour cohesion, saturation, vibrancy and tone, a colourist can manipulate the way an audience emotionally responds.

Colours are often associated with emotions. By identifying what emotion the film makers want, a colourist can highlight a colour or shade to promote that feeling. This emotion and colour relationship was outlined by psychologist Robert Plutchik, who created the Plutchik colour wheel of emotions. Colourists often use it as a reference.

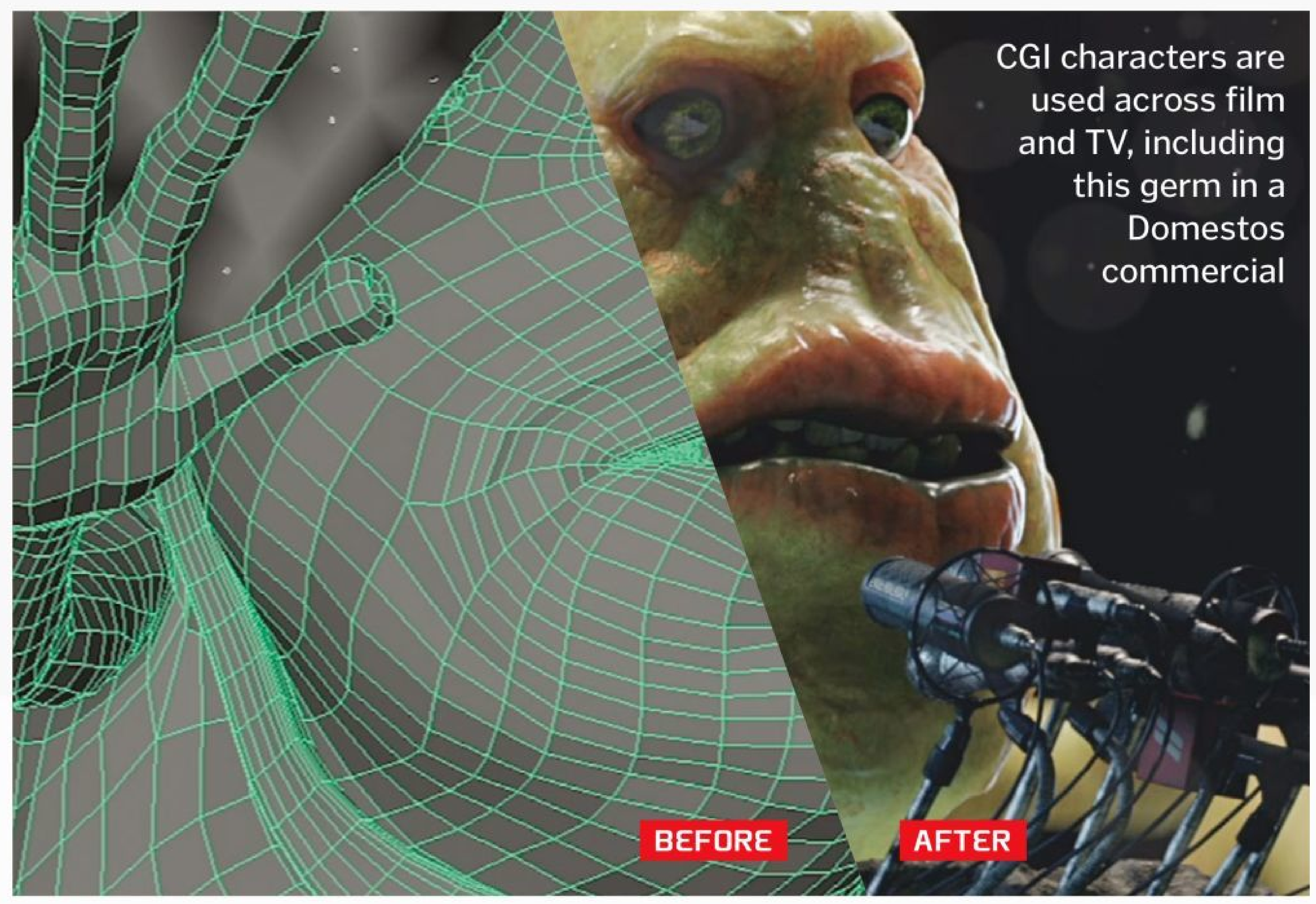


Creating a CGI cast

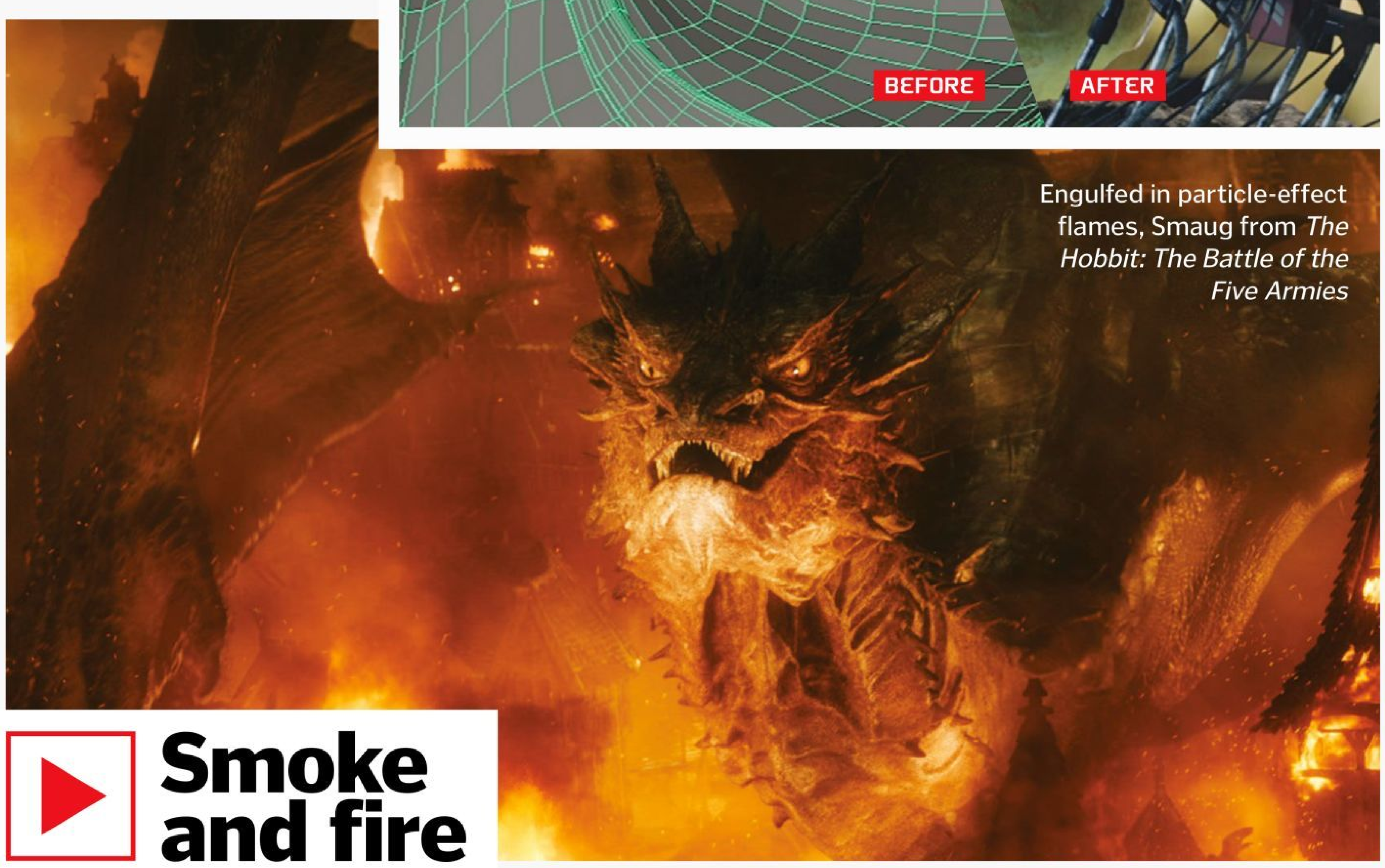
Computer-generated imagery (CGI) is a way to put any digital creation a designer can imagine into a scene. Creating a 3D CGI model can involve a digital version of clay sculpting. From concept art to digitally carving the final creation, CGI can achieve the impossible.

After compiling a series of computer-generated graphics, the final model is then textured, coloured and lighted, keeping in tone with the aesthetics of the movie. For a CGI model to then be animated, each limb, for example, is digitally linked together, almost like adding artificial tendons beneath the model's outer appearance. Known as rigging, this process then allows animators to take the designed model and puppeteer it in a scene.

Although animated, there are different considerations during the production of a CGI character in a live-action movie compared to a full-length animation film. Any CGI creation plays a role within a film, so human actors must interact with their environment on set as if the CGI character is there, while conversely the CGI characters must be puppeteered in a way to give the illusion it's reacting to the actors too.



CGI characters are used across film and TV, including this germ in a Domestos commercial



Engulfed in particle-effect flames, Smaug from *The Hobbit: The Battle of the Five Armies*

Smoke and fire

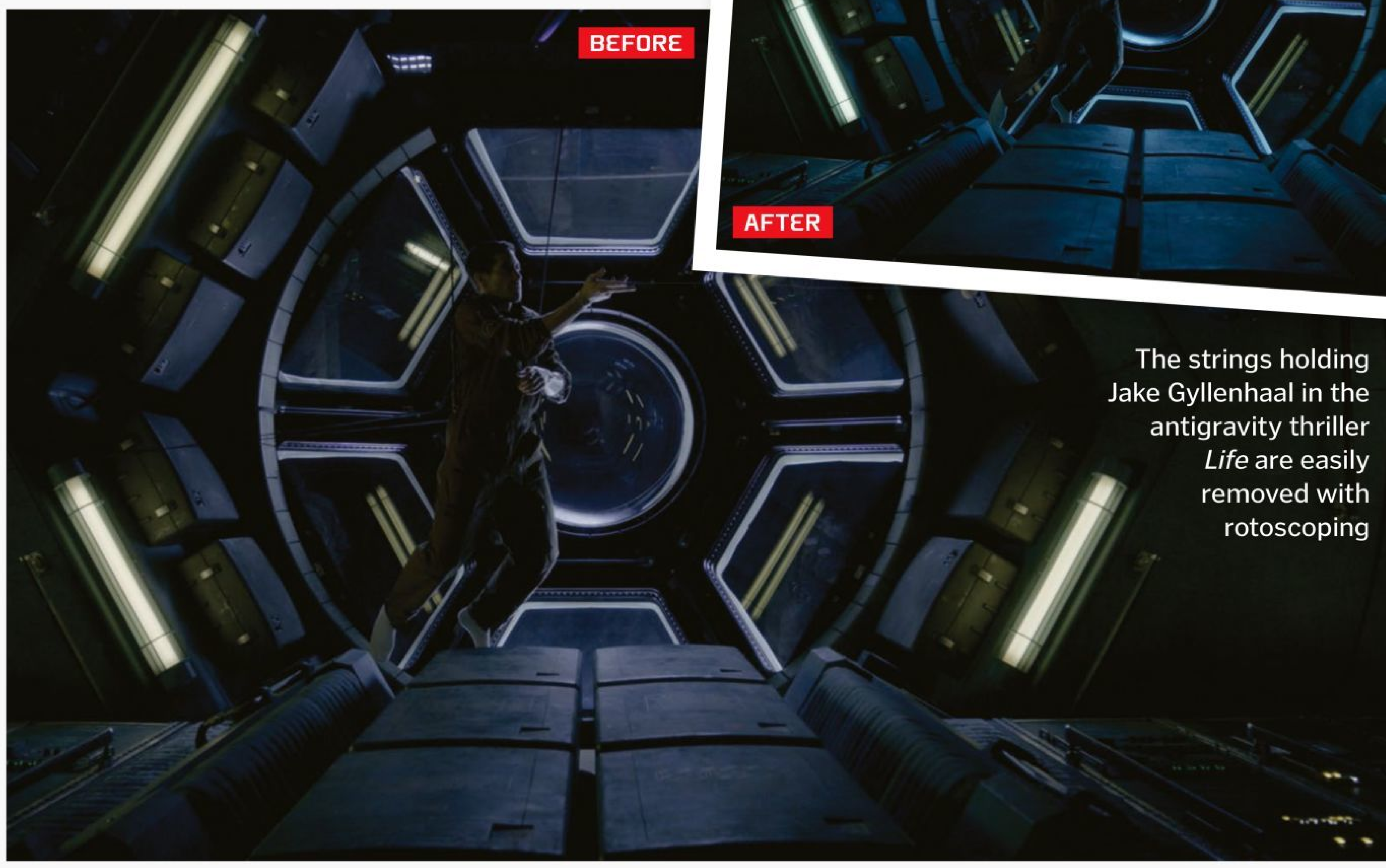
Smoke, fire or water can pose a problem for VFX artists. Impractical to digitally hand-draw or sculpt, artists use particle effects software like Houdini to realise their designs. Designers generate thousands of points, or particles, within the software, and by dictating each particle's movement, size, shape and colour, the simulation of a fire, sandstorm or a waterfall can be created from scratch.

Much like the creation of a CGI character, particle effects require the artist to define the way each particle moves in order to mimic the natural movement of what they are trying to recreate, such as the fluid motion of water.

Cleaning up imperfections

It may seem as though current cinema has moved far beyond the use of strings to suspend flying objects, but in fact movie makers have just got better at scrubbing them off the screen.

Rotoscoping is a method used to isolate part of a frame and either remove or relocate it. By marking the outer parameters of an object, VFX artists are able to cut and paste footage frame by frame. For example, in any science fiction film scene in which a character is experiencing zero gravity (when in real life they are suspended on wires), scenes of their weightless motion can be cut out and pasted onto another background. This visual effect, however, is a time-consuming endeavour, as films are often shot at 24 frames a second.



The strings holding Jake Gyllenhaal in the antigravity thriller *Life* are easily removed with rotoscoping

© Outpost

VFX elements surrounding a moving character are tracked and follow the motion of the camera

© Outpost

© Outpost

"Combining the two exposed films resulted in a sequence that left audiences spellbound"

Seamless effects

Visual effects are only as effective as their ability to seamlessly integrate with a scene. Their value is directly tied to the audience's ability to believe that something computer-generated could really be interacting with live-action elements.

This is where tracking comes in handy. Tracking is the process in which all the VFX elements in a shot follow the movement of an object, person or the direction of the camera in the original footage. If the movements of the added VFX elements are not in sync with the movement of the camera, the combination of the two feels disjointed, and the desired illusion is suddenly broken.

The magic of Méliès

The art of visual effects is not a concept new to the 21st century, nor the 20th. In the late 1800s magician and future film revolutionary Georges Méliès put the wheels in motion for visual effects. Long before the use of green screen keying, Méliès created a technique known as 'matte' to composite different footage.

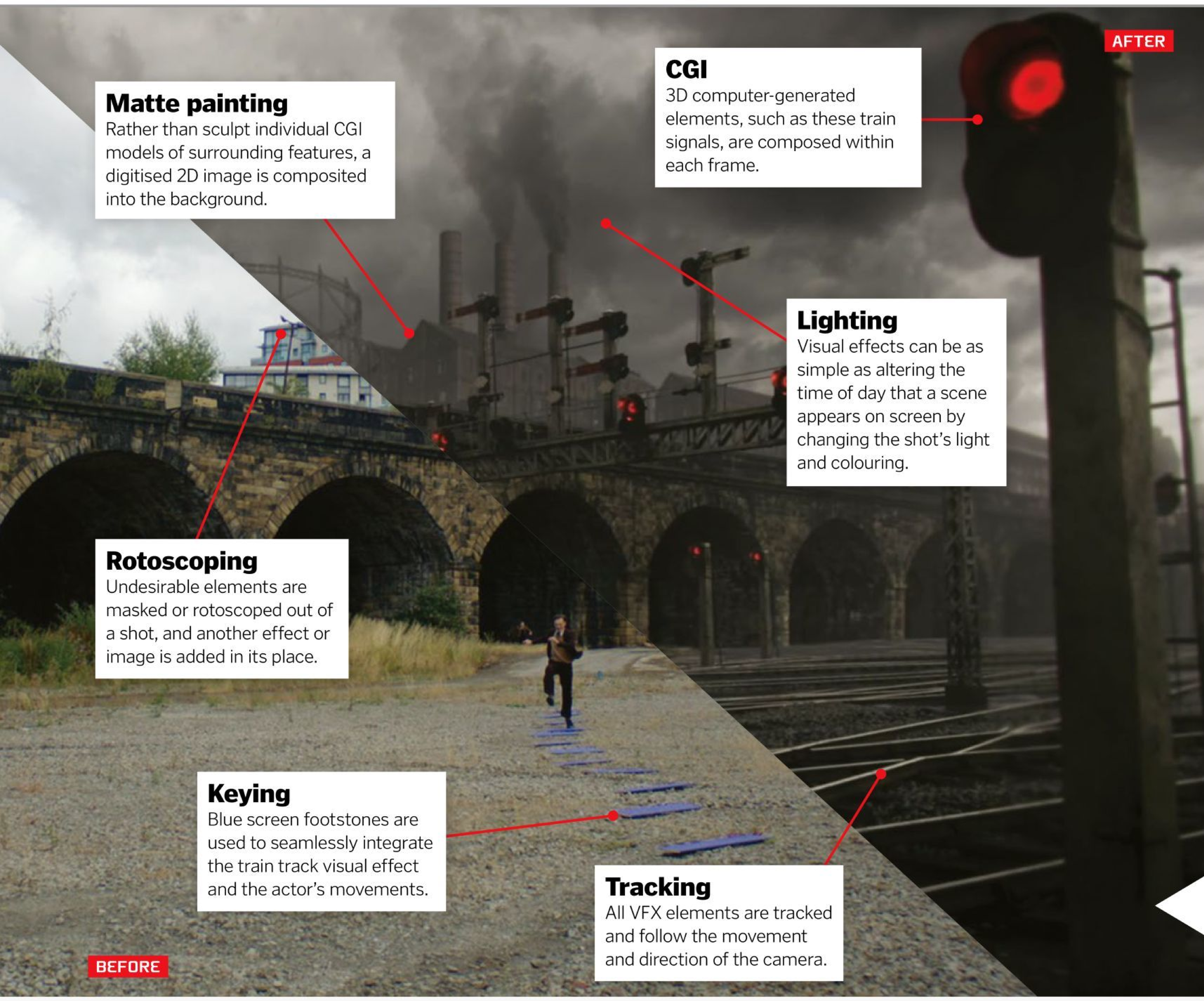
In his 1898 silent film *The Four Troublesome Heads* (*Un Homme De Tête*) Méliès appears to take his head off his body and place it on a table, repeating the impossible feat three times. In this original trick of early film, Méliès used a pane of glass painted with a black matte finish to block out his head. Rewinding the film, he then placed matte black over everything other than his head. Combining the two exposed films resulted in a sequence that left audiences spellbound.

© Alamy

Georges Méliès used pioneering techniques to create spectacular illusions on film

Dissecting a scene

Frame by frame, how VFX experts fill a single scene with different visual effects



Piecing the puzzle together

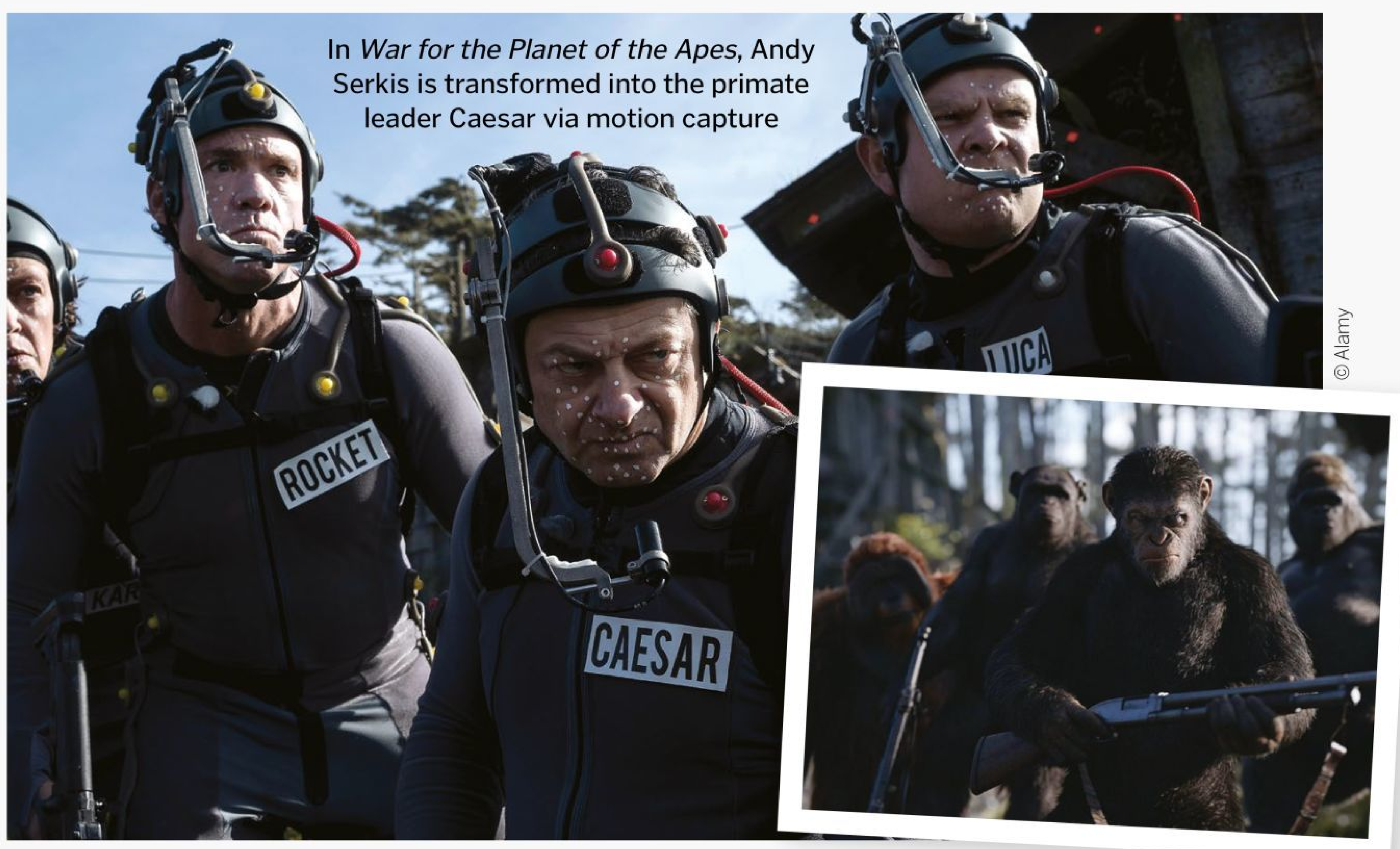
This is the process whereby all of the VFX elements are brought together. Like a digital jigsaw, each effect and piece of film footage can layer over one another, a method known as compositing. This process can be as straightforward as dropping in a new background, while in heavy VFX scenes several elements need to be compiled and composited, creating several layers to form the final product.

Body swapping

Motion capture brought to life characters such as the inhabitants of Pandora in *Avatar* and the beast from *Beauty and the Beast*. Combining real life and the digital world, 3D motion capture transforms actors into their computer-generated characters.

To make this transformation, actors wear a capture suit covered in small dots. These dots, known as tracking position markers, act as reference points to track the actor during a scene. In the VFX process, these points can be mapped onto the virtual skeleton of a computer-generated character, such as Gollum from *The Lord of the Rings*.

Digitally stitching both the real-life actor to their CGI character, the two appear as one on screen. Motion capture can also be used to add VFX to separate areas of the body, such as the hands or face, rather than the entire body.



In *War for the Planet of the Apes*, Andy Serkis is transformed into the primate leader Caesar via motion capture

Visual effects through the years

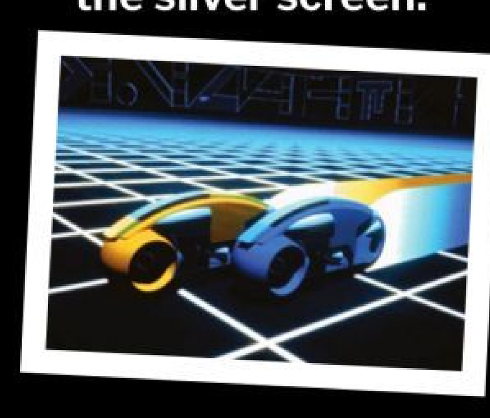
Here are some key moments in the history of movie visual effects

1973
In Michael Crichton's *Westworld* the lead character's 'robovision' is the first example of 2D CGI.

1976
The first 3D computer graphics are found in *Westworld*'s sequel, *Futureworld*. The main android's head and hands are digitally created.

1977
The Death Star attack briefing scene in *Star Wars IV* sees the first example of 3D wireframe graphics.

1982
In *Tron*, the light cycle races were the first extensive 3D CGI sequences seen on the silver screen.



1985
Combining digital and live action, Pixar's *Young Sherlock Holmes* creates a stained glass warrior that leaps straight from the window to the ground.

1989
The first example of CGI water effects appears in *The Abyss* in the form of a morphing sea monster.

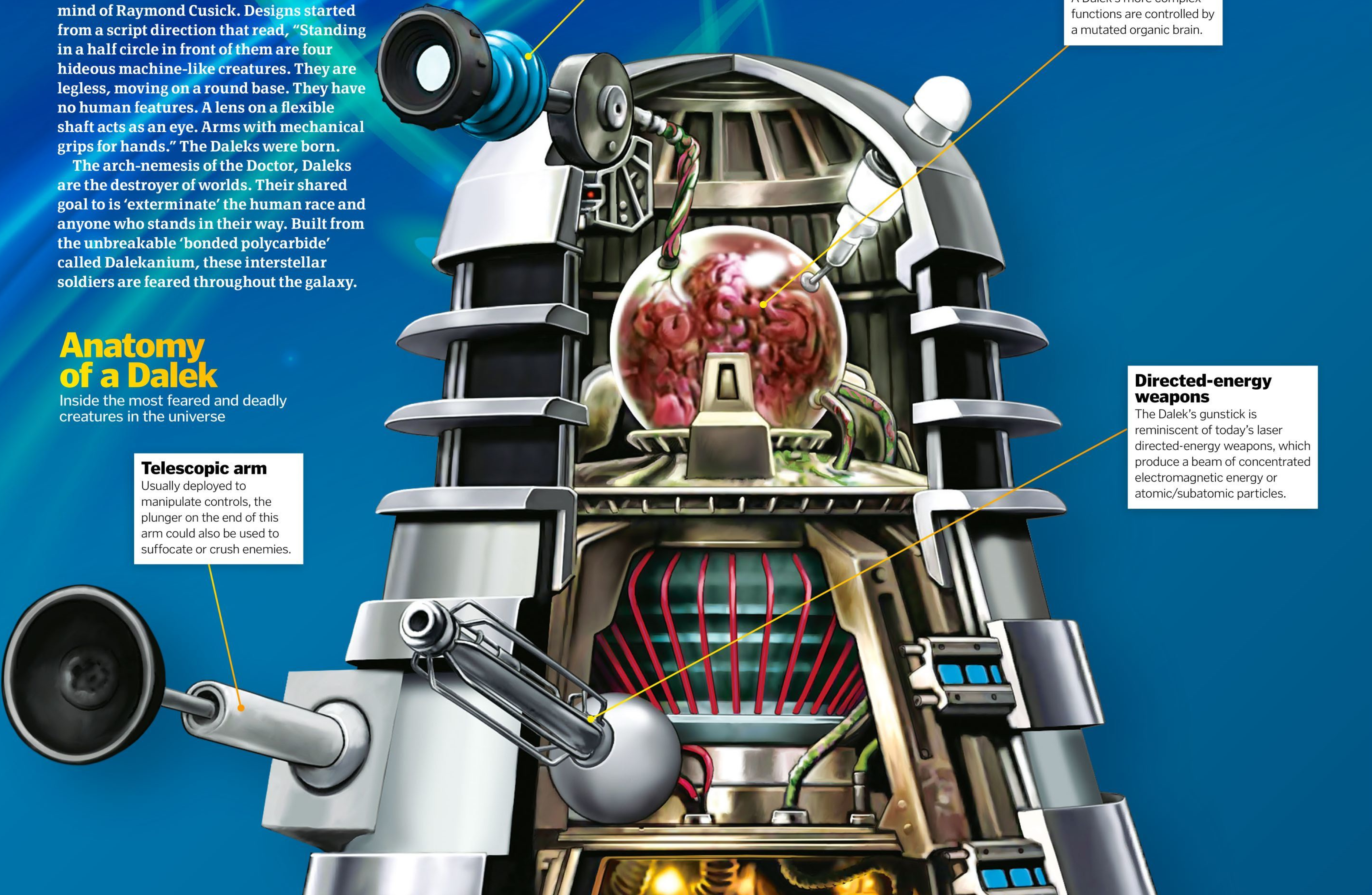
DESIGNING THE DALEKS

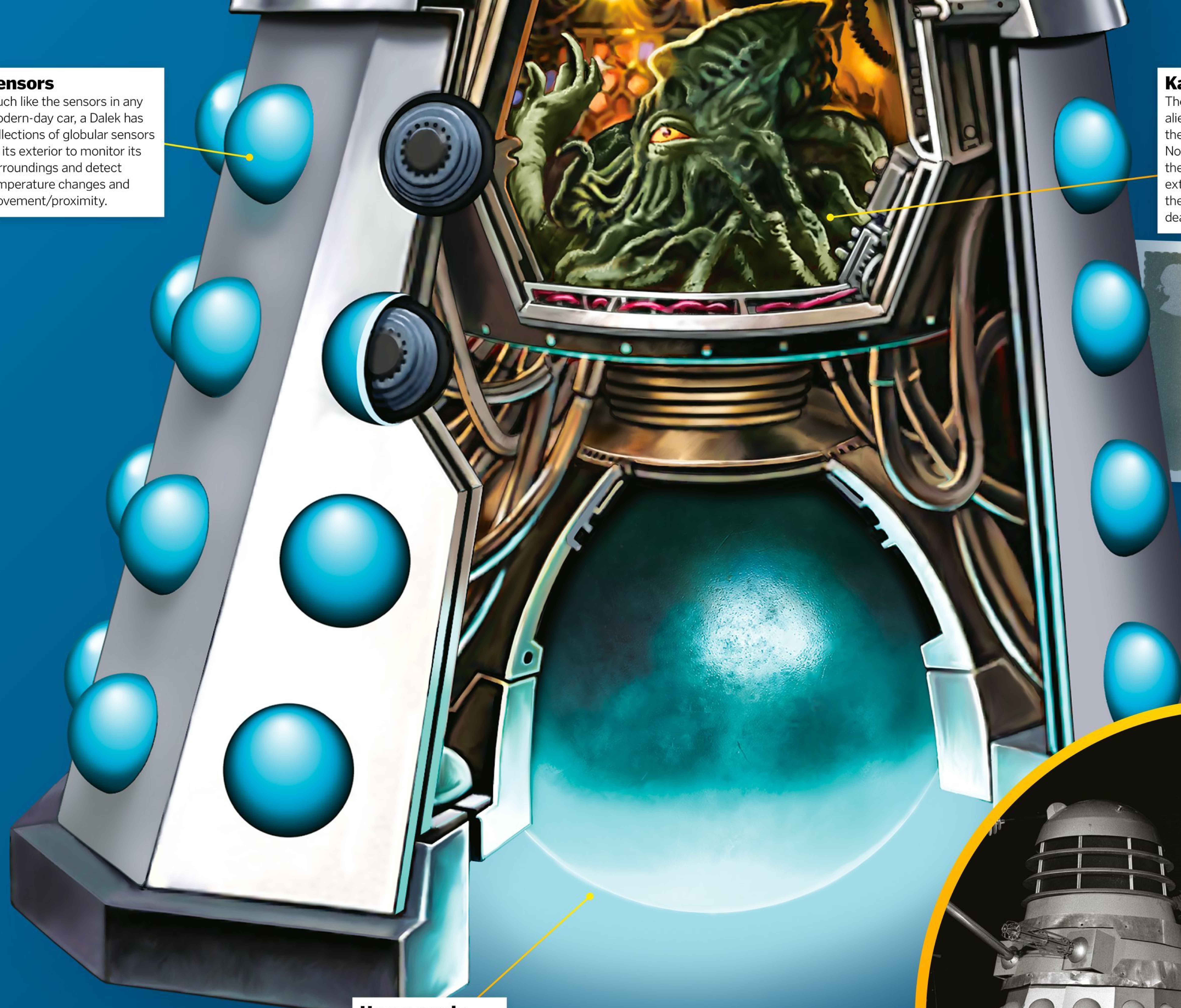
From the writer's room to the planet Skaro, Daleks were brought to life in the creative mind of Raymond Cusick. Designs started from a script direction that read, "Standing in a half circle in front of them are four hideous machine-like creatures. They are legless, moving on a round base. They have no human features. A lens on a flexible shaft acts as an eye. Arms with mechanical grips for hands." The Daleks were born.

The arch-nemesis of the Doctor, Daleks are the destroyer of worlds. Their shared goal to is 'exterminate' the human race and anyone who stands in their way. Built from the unbreakable 'bonded polycarbide' called Dalekanium, these interstellar soldiers are feared throughout the galaxy.

Anatomy of a Dalek

Inside the most feared and deadly creatures in the universe



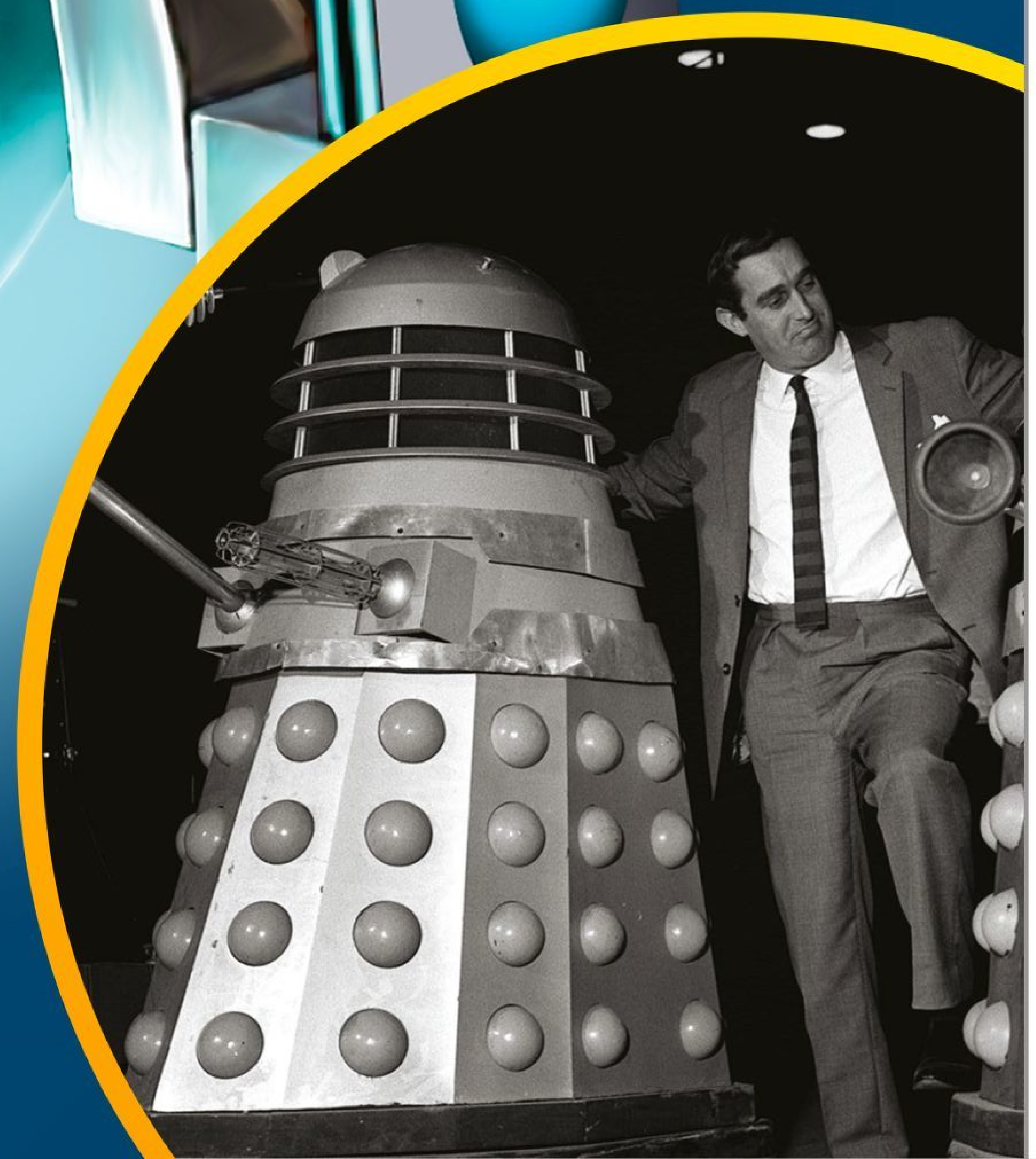


Sensors
Much like the sensors in any modern-day car, a Dalek has collections of globular sensors on its exterior to monitor its surroundings and detect temperature changes and movement/proximity.

Kaled mutant
These octopus-like aliens originate from the planet Skaro. Normally reliant on their armoured exterior for protection, they are almost as deadly without it.

Hover-mode
Daleks are also equipped with anti-gravitational discs in order to levitate off the ground.

Doctor Who is well established within British culture – a Dalek featured on a set of Millennium stamps celebrating the 20th century



Science-fiction writer Terry Nation (pictured) first created the Daleks, before Raymond Cusick brought them to life

HEROES OF... TECHNOLOGY

Martin Cooper posing with the original model of the mobile phone he invented

© Alamy

The DynaTAC was the height of innovation when it was released commercially in the 1980s

© Alamy

A life's work

The father of the mobile phone

1928
Marty Cooper is born on 26 December in Chicago, Illinois, to Ukrainian Jewish parents.

1950
Cooper graduates from the Illinois Institute of Technology with a degree in electrical engineering.

1950–53
Serving in the US Navy, Cooper fights in the Korean War.

1954
After a brief stint at Teletype Corporation, Cooper is headhunted by Motorola and joins the company as an engineer.

1972
As AT&T begin a project on the mobile phone, Motorola sets up a rival project and puts Cooper in charge.

He invented the cell phone

Meet Martin 'Marty' Cooper, a communications trailblazer

Sometimes invention is born out of necessity – sometimes it's born out of corporate rivalries. The latter is certainly more accurate when it comes to the invention of the mobile phone. There was so nearly a different name attached to this monumental creation, and the company its team worked for would have been AT&T. Instead, it was Marty Cooper's team at Motorola.

After getting his degree in electrical engineering from the Illinois Institute of Technology in Chicago and serving in the US Navy during the Korean War, Cooper found himself working for Teletype Corporation for a short while before moving on to Motorola in 1954. During his time there he was known as an innovator, working on projects that included the first radio-controlled traffic light system, patented in 1960, and the first handheld police radios, which were introduced in 1967. In fact, his contribution to the company was so great that he was made vice president and director of research and development in 1978. This promotion was probably in no small part due to his work earlier in the decade.

When Motorola found out that AT&T was putting a team together to invent the first mobile phone, the response was simple: the company was going to put together its own team and invent it first to avoid AT&T from dominating the market. Cooper was placed in charge, and they all got to work. Ideas were bounced around and prototypes made before, finally, they had created the Dynamic Adaptive Total Area Coverage phone, or DynaTAC. At 23 centimetres tall, it weighed 1.1 kilograms and it could be used for 35 minutes of talk time before the battery died, and it took about ten hours to fully charge. While it may not seem very impressive today, in the 1970s, that was a big deal.

Before it could be officially announced to the world that the phone had been invented, however, it needed to be tested. Cooper knew just how he was going to do so – a few days before the press conference, he stood on a street corner in New York City with the phone. He dialled a number and made the first ever call from a mobile phone. The man at the other end of the call was none other than Joel Engel, the leader of AT&T's rival project, the one that spurred Motorola into action in the first place. Now sure that it was in complete working order, Cooper unveiled the DynaTAC on 3 April 1973.

Work hadn't been finished, though – the next decade was spent refining the model, and the DynaTAC 8000x, a version suitable for consumers, went on sale in 1983. At $3,995 it wasn't exactly the most affordable piece of equipment, but it was a success nonetheless, and mobile phones have now revolutionised the world. While these early models were only good for short conversations, the technology evolved into what we know today – mobile phones can now access the internet, provide entertainment and so much more.

THE BIG IDEA

From home, to cars to becoming a truly mobile phone

Marty Cooper hadn't set out to invent the mobile phone, but he was an expert in wireless communication technology. What he and his team designed was nothing short of revolutionary. While a sort of mobile phone had existed before, attached to cars, trains and other vehicles, this would be the first that could be carried anywhere. Over the ten years between making the prototype and launching the consumer version of the DynaTAC, it was refined and the battery was improved so that talk time increased to an hour, and there was enough storage for 30 phone numbers.

The DynaTAC 8000x was released in the US in 1983 and the UK in 1985

5 THINGS TO KNOW ABOUT… MARTY COOPER

1
29 years at Motorola
Cooper worked his way up to becoming vice president and director of research and development having working on the mobile phone project.

2
Working for the competition
Before joining Motorola in the 1950s and working against AT&T to invent the mobile phone first, Cooper had actually been employed by Teletype Corporation, an arm of AT&T.

3
Prize-winning inventor
Cooper has earned many awards in his time, including the Charles Stark Draper Prize from the US National Academy of Engineering and the Marconi Prize, both in 2013.

4
Wireless communication for life
After leaving Motorola in the 1980s, Cooper founded Cellular Business Systems, Inc. and then Dyna, LLC., both of which focused on aspects of wireless communications.

5
War veteran
Cooper served in the US Navy as a submarine officer during the Korean War, but he didn't get into radio technology until he began working at Motorola, a year after the war ended.

1973
The new DynaTAC is unveiled in New York City. To check it works, Cooper phones the lead engineer on AT&T's team.

1978–83
Working his way up through the ranks, Cooper becomes vice president of research and development at Motorola.

1983
In the year the DynaTAC 8000x goes on sale, Cooper leaves Motorola and founds his own company, Cellular Business Systems, Inc.

1986
Cooper sells his company to Cincinnati Bell for $23m. He then founds another company with his wife, Arlene Harris, called Dyna, LLC.

"At 23 centimetres tall, it weighed 1.1 kilograms and it could be used for 35 minutes of talk time"

Embankments will be created to mask the shaft feeding sewage into the tunnel below

Explore London's super sewer

Discover the tunnel being built deep beneath the Thames River and how it's going to prevent poo from contaminating the water

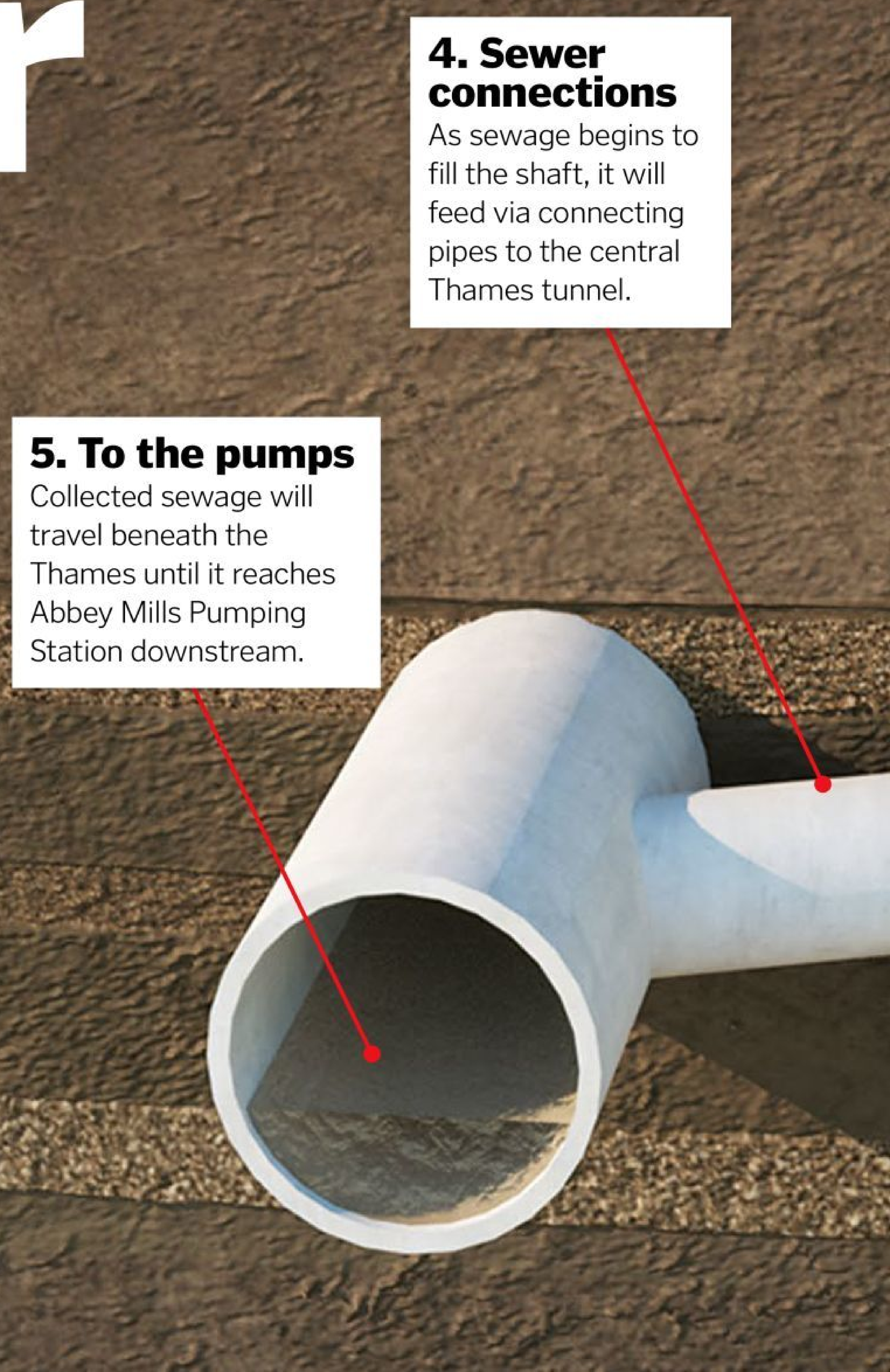
Words by **Scott Dutfield**

In the mid 1800s, London's Victorian sewer system was built to combat the growing outbreaks of cholera and typhoid fever that were killing thousands of Londoners. It was designed by chief engineer Joseph Bazalgette, used around 318 million bricks and spanned the entire city.

Although the Bazalgette sewer system has served the residents of London well over the past 150 years, it hasn't been without issues. Originally built to support the waste of 4 million people, the capital city is now home to over 8 million people and rising, putting pressure on the city's sewers. Currently the sewers are contending with 1.25 million tons of human waste each day.

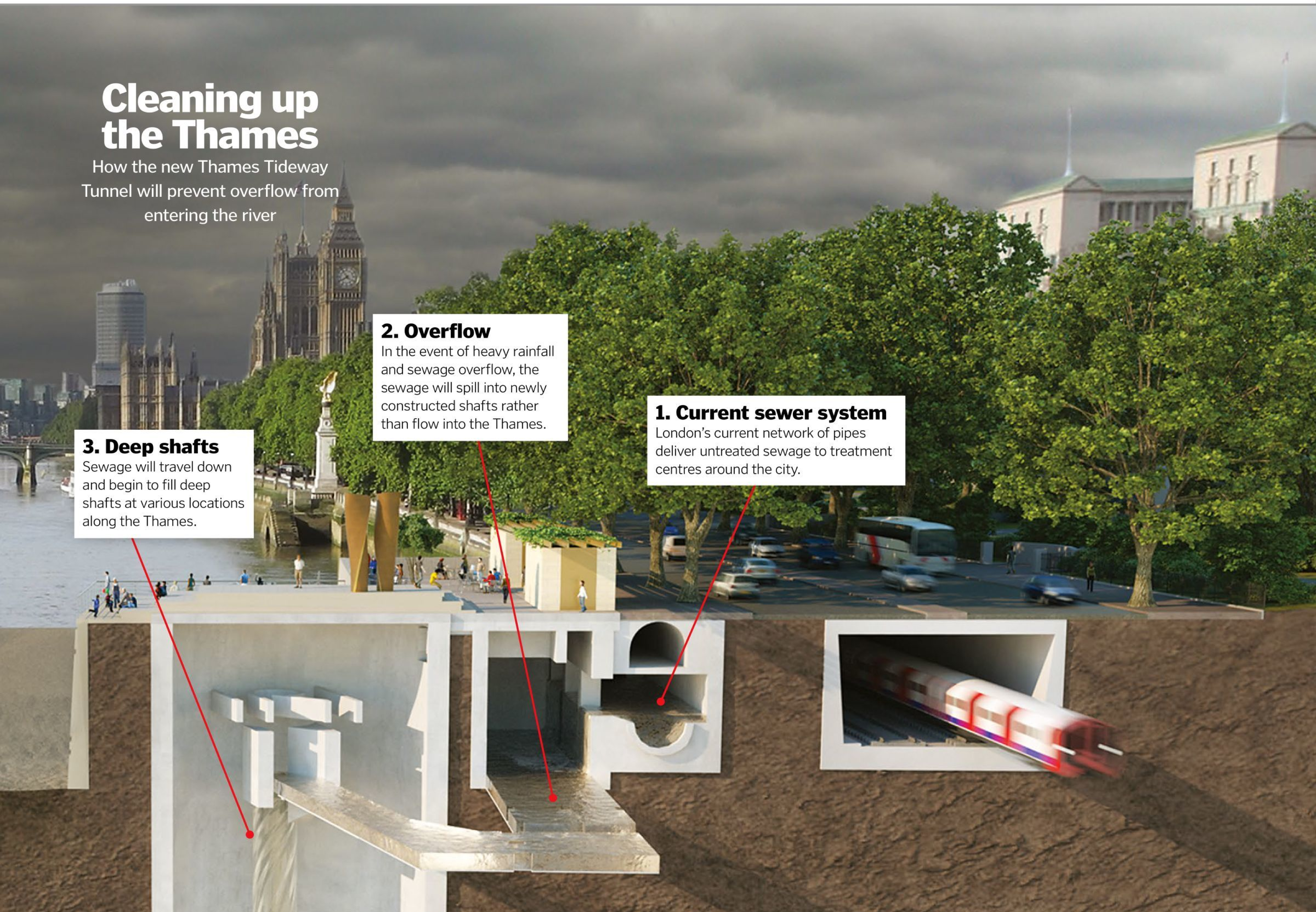
As a fail-safe to prevent sewage from spilling onto the streets of London, the current network of pipes is connected to several overspill pipes that deposit waste into the water of the Thames. As London's population continues to grow, millions of tons of waste contaminate the river's water.

It is this overspill design that has prompted Tideway, an engineering company, to create the Thames Tideway Tunnel. As an improved



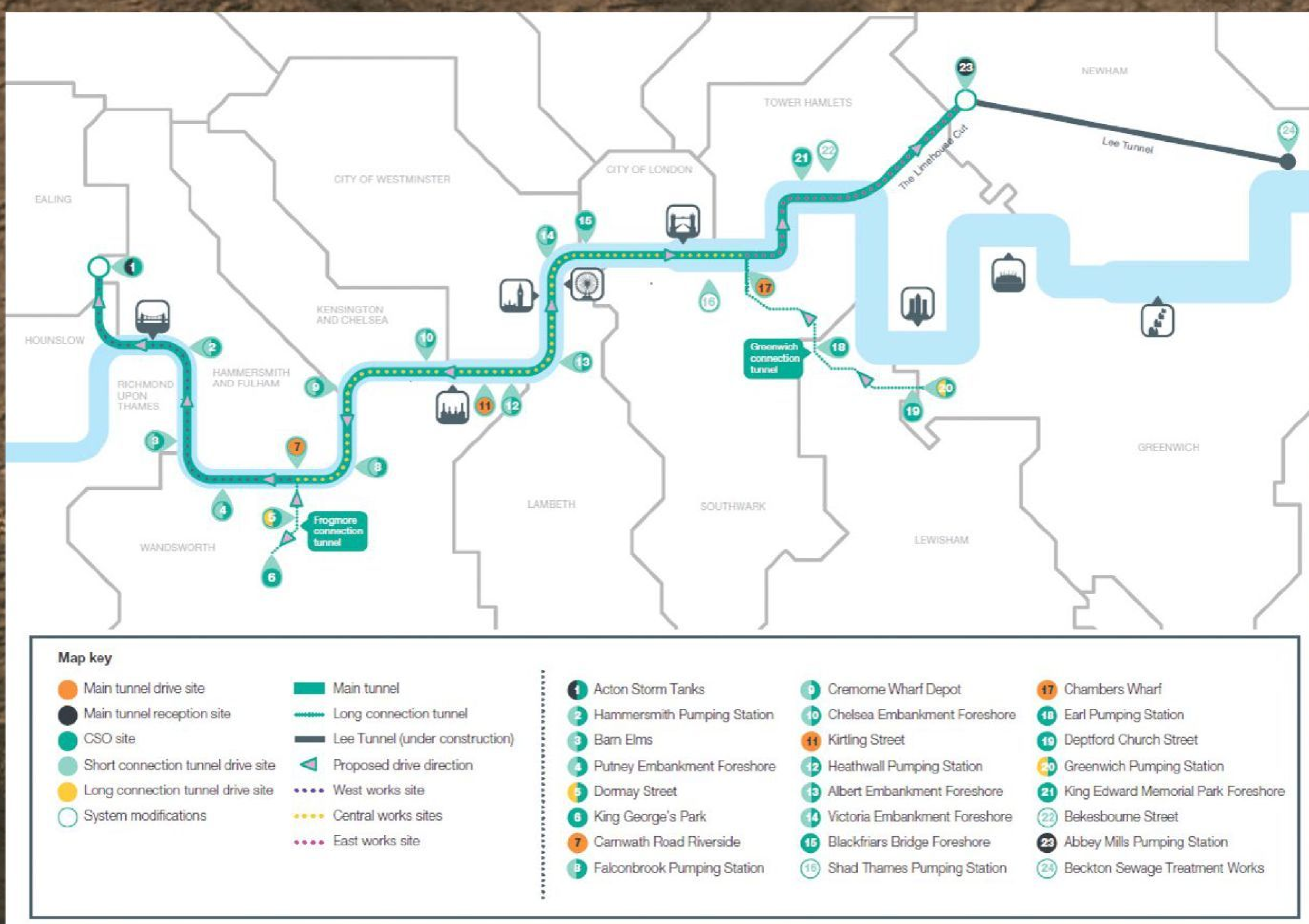
Cleaning up the Thames

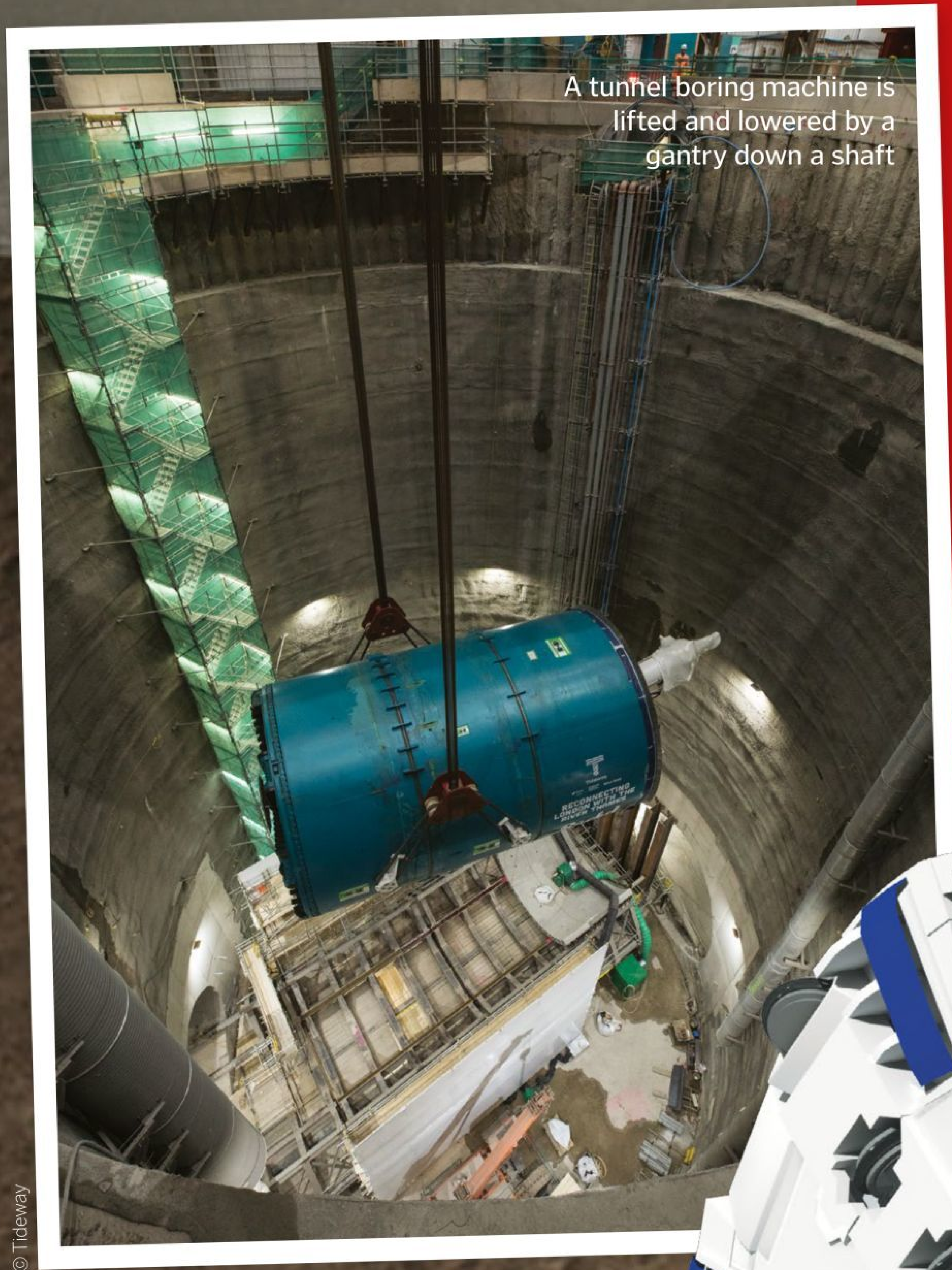
How the new Thames Tideway Tunnel will prevent overflow from entering the river



Subterranean super sewer

The new tunnel's route takes it from one side of London to the other





A tunnel boring machine is lifted and lowered by a gantry down a shaft

© Tideway

addition to the Victorian sewers, the new super sewer is a prime example of engineering precision.

Beginning at Acton Storm Tanks in Ealing, the 25-kilometre-long tunnel will burrow beneath and follow the Thames until reaching Abbey Mills Pumping Station in Newham, London. Sewage collected throughout the tunnel will be sent down the Lee Tunnel, reaching its final destination at the Beckton Sewage Treatment Works.

In order to shape the Thames Tideway Tunnel, massive machinery has been brought in to carve into the rock deep below the river. Known as a tunnel boring machine (TBM), this burrowing behemoth pushes its way through bedrock, shaping the tunnel as it goes. What lies in the wake of the TBM's tunnelling force is tons of displaced rubble. Continually feeding through the belly of the metal beast, excavated material or slurry is carried on conveyor belts back to the surface.

Construction of the tunnel will create 4 million tons of rock and rubble that will need to be removed. Tideway is utilising the Thames to transport the material to landfill sites, via barges that can carry the equivalent of 50 heavy goods lorries. The rubble will then be used to cap off landfill sites, which will then be turned into nature reserves.

Giant Thames worm

Officially known as a tunnel boring machine (TBM), this mammoth vehicle can cut through bedrock, clearing the way for the new super sewer under the Thames

Propulsion
The TBM moves with the help of hydraulic rams that push against the newly placed tunnel ring, moving it forward.

Cutter head
Made of steel, this circular, 8m mouth of earth-cutting teeth rotates, breaking down soil and rock in order to carve out the tunnel.

48 hours
The time taken to empty the tunnel when full

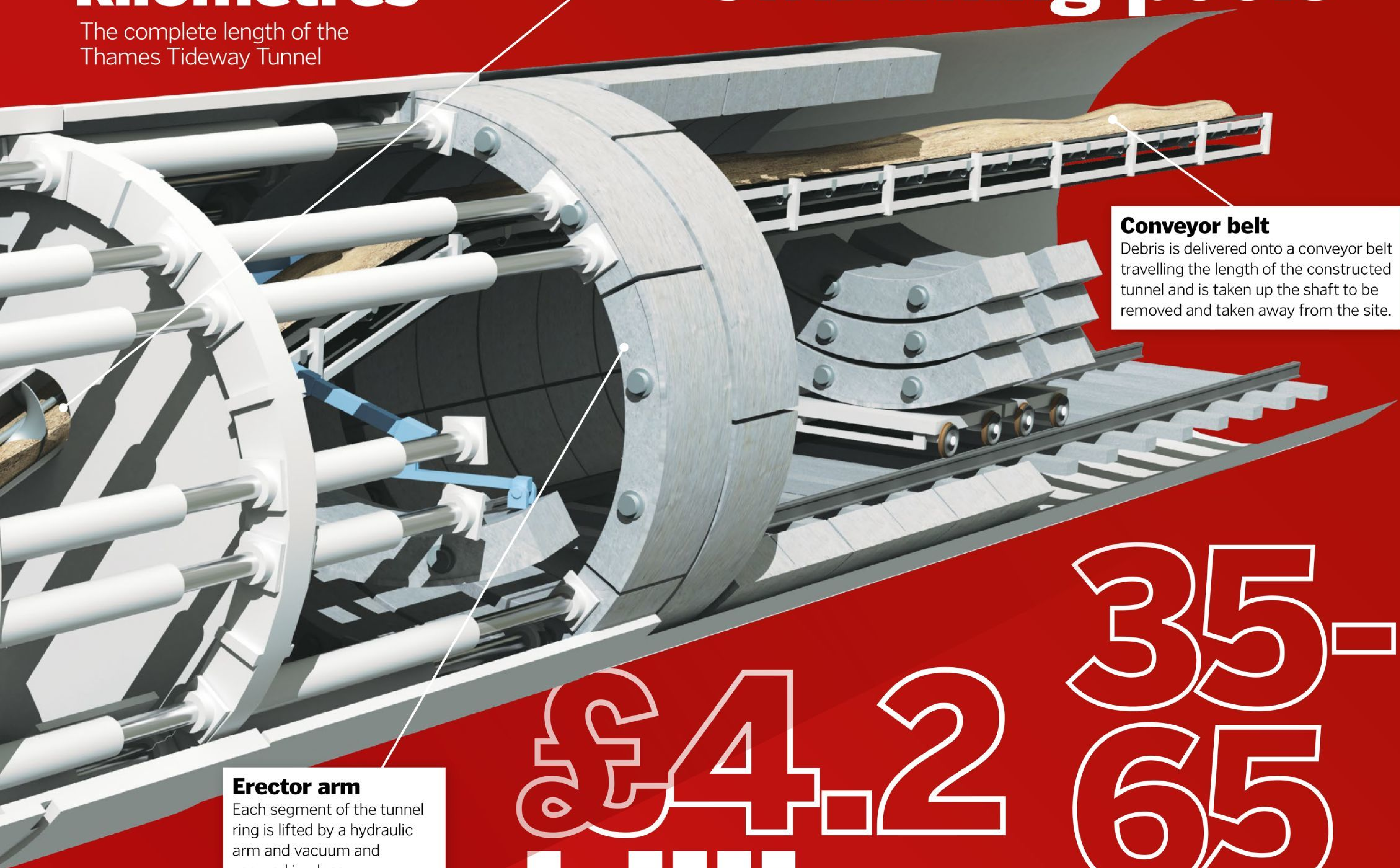
7.2 metres
The width of the tunnel

25 kilometres

The complete length of the Thames Tideway Tunnel

The Thames Tideway Tunnel's storage capacity is equivalent to

600 Olympic-sized swimming pools



£4.2 billion

Estimated cost to construct the new tunnel

35-65 metres

The depth below the ground the Thames tunnel will run

Constructing London's sewer system

1848
The Metropolitan Commission of Sewers is established to find a solution to London's serious sewage problem.

1858
Following a heatwave that results in the city's famous 'Great Stink', parliament approves the construction of a new London sewer system.

1859
Work begins on a new centralised sewer system, designed by the engineer Joseph Bazalgette.

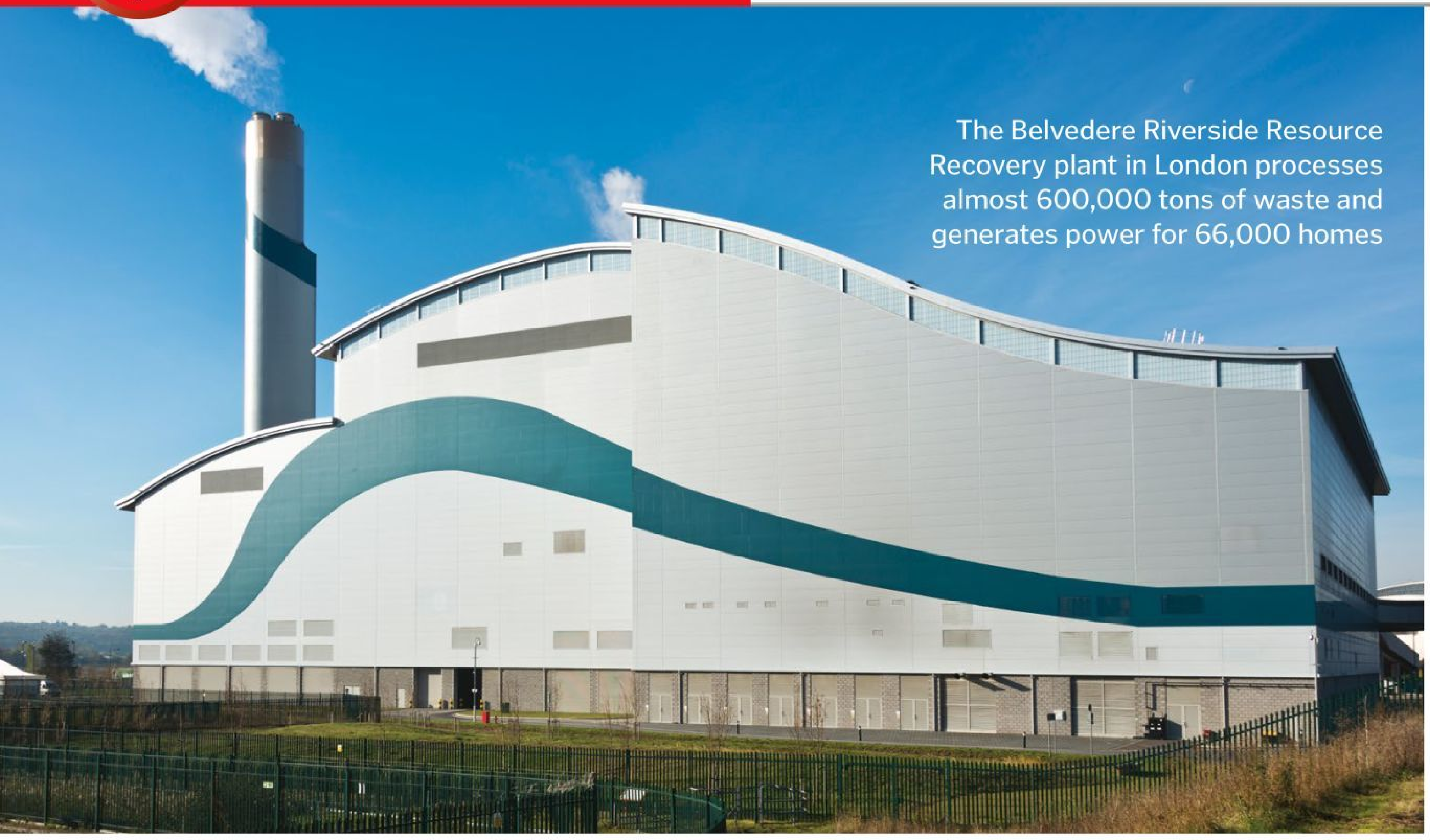
1865
The first phase of the Bazalgette sewer system is opened, comprising of 1,770km of street sewers and around 130km of underground main brick sewers.

2014
Plans are approved to construct the Thames Tideway Tunnel.

2016
Preliminary work begins to facilitate the tunnel's construction.

2018
The construction of the tunnel begins at Hammersmith Pumping Station.

2024
The target deadline for the completion of the Thames Tideway Tunnel.



The Belvedere Riverside Resource Recovery plant in London processes almost 600,000 tons of waste and generates power for 66,000 homes

Flames roar to over 1,000°C inside a household waste incinerator at an energy recovery unit in France

What's inside a waste incinerator?

These hulking machines burn hot enough to melt metal and send rubbish up in smoke

The UK alone produces approximately 220 million tons of waste annually, a figure that contributes to a global yearly total that hit 1.3 billion tons in 2017. Experts have predicted that this number could reach 2.2 billion by the year 2025 as urbanisation continues to increase. All of this waste has to be collected and handled safely, and one method that is commonly used is incineration.

Running at around 750 degrees Celsius, incinerators come in a variety of designs (including those fitted with a rotary kiln), but they all share the same purpose – to safely destroy waste and treat the by-products of this process in order to mitigate the chances of potentially hazardous materials being released into the atmosphere.

This is achieved by first burning the municipal materials collected and then inspecting the ash produced as a result. This ash comes in two forms: fly (or flue) and bottom ash. The latter is the least dangerous as it clings to the searing sides of the incinerator. This type of ash is inspected with a magnet to retrieve any valuable metals for recycling. However, the finer variety of fly ash can be unsafe to expel from chimneys, as it often contains gaseous traces of heavy metals such as lead and mercury. Fly ash is therefore passed through a scrubbing device to treat and remove any harmful substances from the exhaust before it is released.

There are currently 44 waste incinerators in operation in the UK, and many environmentalists are concerned about the emissions released from incinerators. Another disadvantage is the high cost required to keep an incinerator working, but with plans in place to double the number of these rubbish burners in the UK, it seems that waste incineration will continue to be used in the near future.

Your burning question

What happens to our rubbish when it's incinerated?

Dubai has set itself a target of reducing its landfill waste by 75 per cent

Dubai's mega incinerator

In January 2018 Dubai announced its intentions to construct what will be the biggest waste-to-energy plant on Earth. Scheduled to be built in Warsan, United Arab Emirates, the plant will be capable of processing 2 million tons of waste a year, which makes up 60 per cent of the waste produced by the city. This will generate enough electricity to power approximately 120,000 homes in the surrounding district.

Waste collected from around Warsan will be burned at a temperature of 1,200 degrees Celsius in order to thermally treat any potentially dangerous gases contained within the waste, before any remaining fly ash can be released via the plant's chimney.

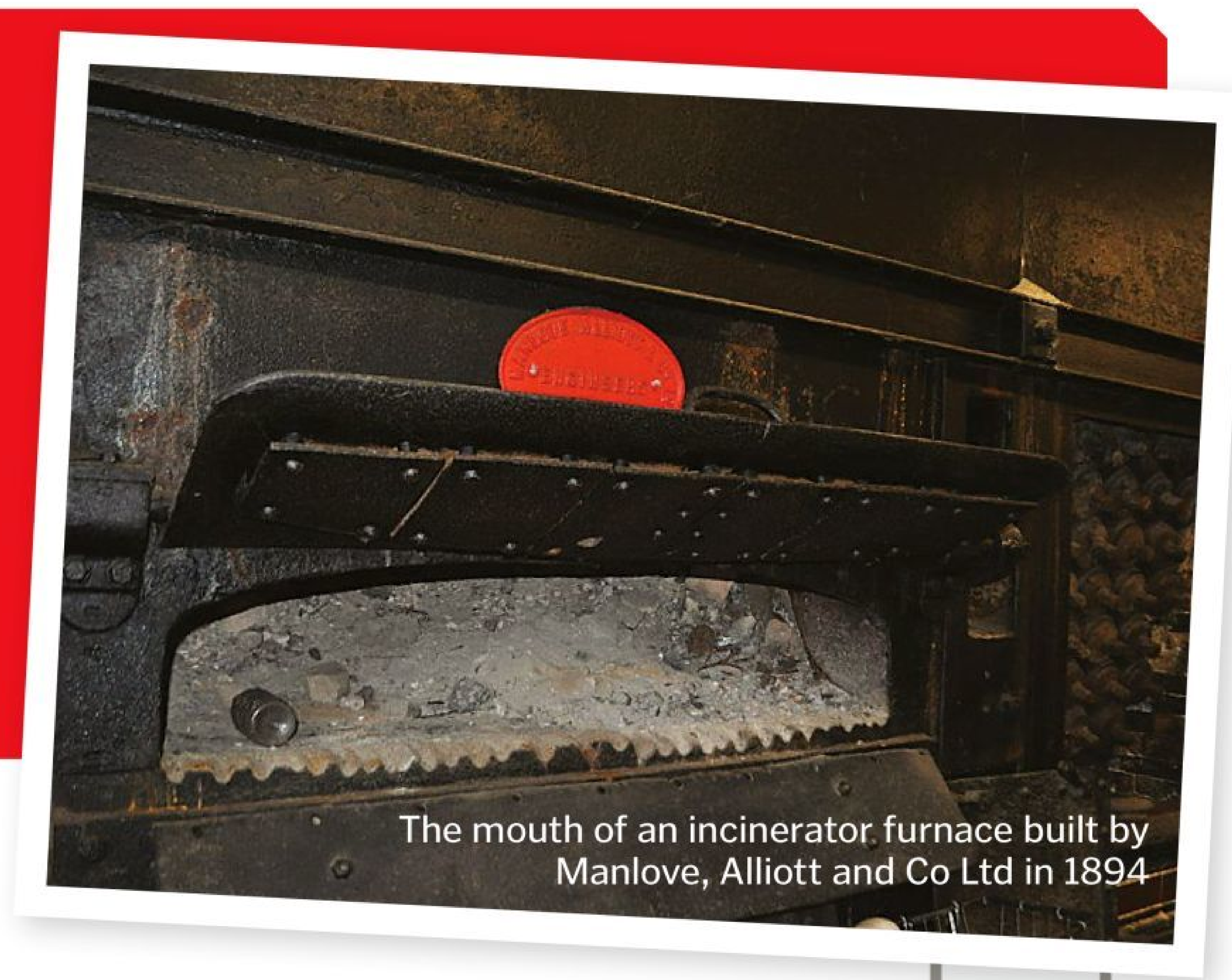
A potential rival to this superplant has been given the green light in Shenzhen, China. Located in China's southeast, Shenzhen's 20 million inhabitants produce 15,000 tons of waste a day, a third of which will be incinerated within the city's new energy plant upon completion in 2020.

Alfred Fryer – incendiary pioneer

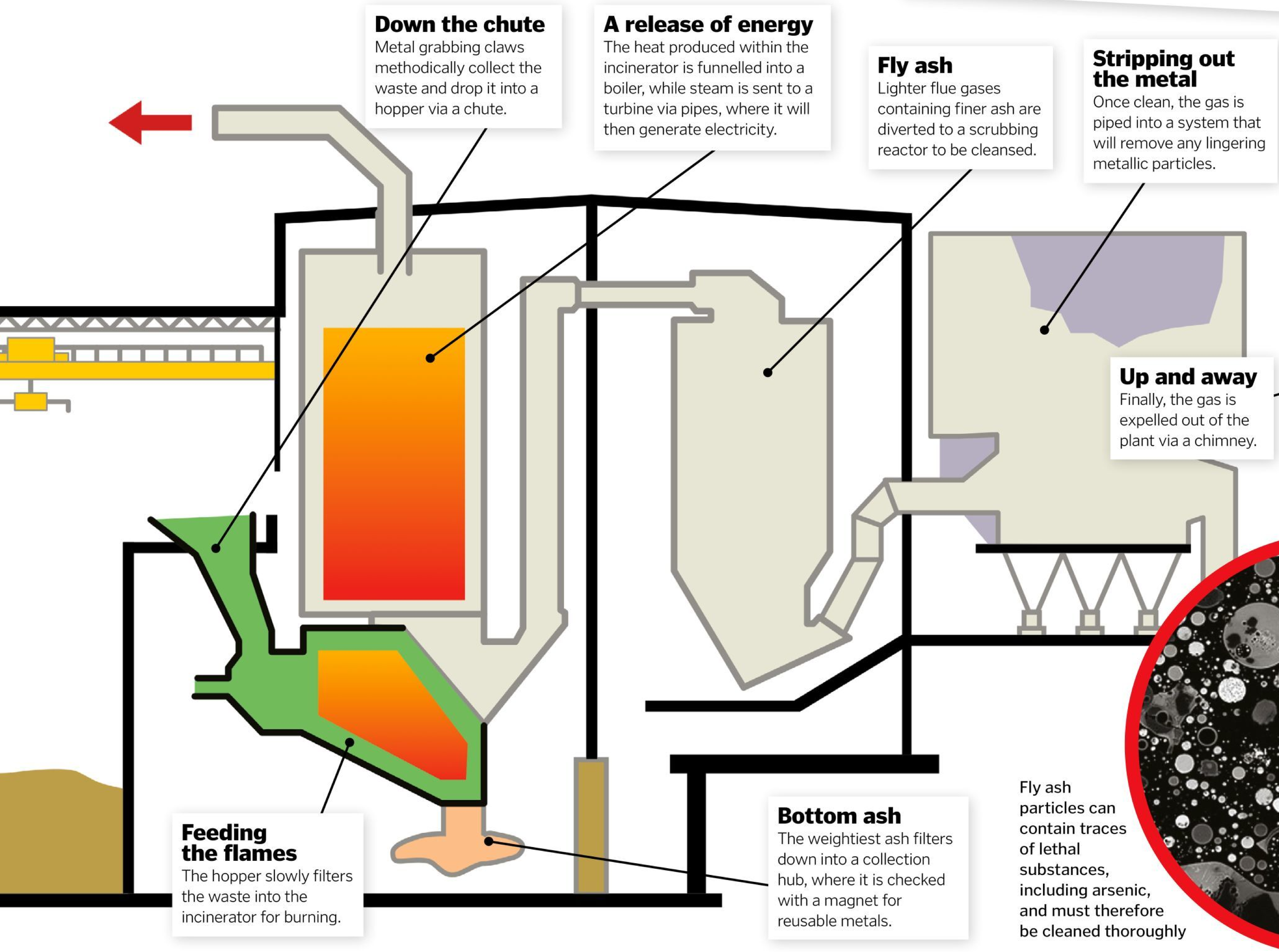
Born in Yorkshire, England, in 1831, Alfred Fryer would one day patent an idea that would revolutionise waste management in the industrialised West, but first he would take an unusual – and rather sweet – career path.

Appointed head of the Manchester-based sugar refinery Fryer, Benson and Forster while in his early 30s, in 1865 Fryer invented a machine known as a 'concretor' designed to solidify sugar cane juice before it was shipped abroad. He then followed this creation up in 1874 while working at Manlove, Alliott and Co Ltd with a patent for a 'destructor', which would later be recognised as the first ever commercial waste incinerator.

A father of four, the inventive Fryer often conducted business in far-flung locations, and he visited destinations including Egypt and Palestine prior to his death in Cheshire in 1892.



The mouth of an incinerator furnace built by Manlove, Alliott and Co Ltd in 1894



Fly ash particles can contain traces of lethal substances, including arsenic, and must therefore be cleaned thoroughly

50%
The UK is aiming to recycle half of its household waste by 2020.

330m tons
Annual disposal capacity of the world's waste-to-energy plants.

2,450
Number of waste-to-energy plants currently in operation globally.

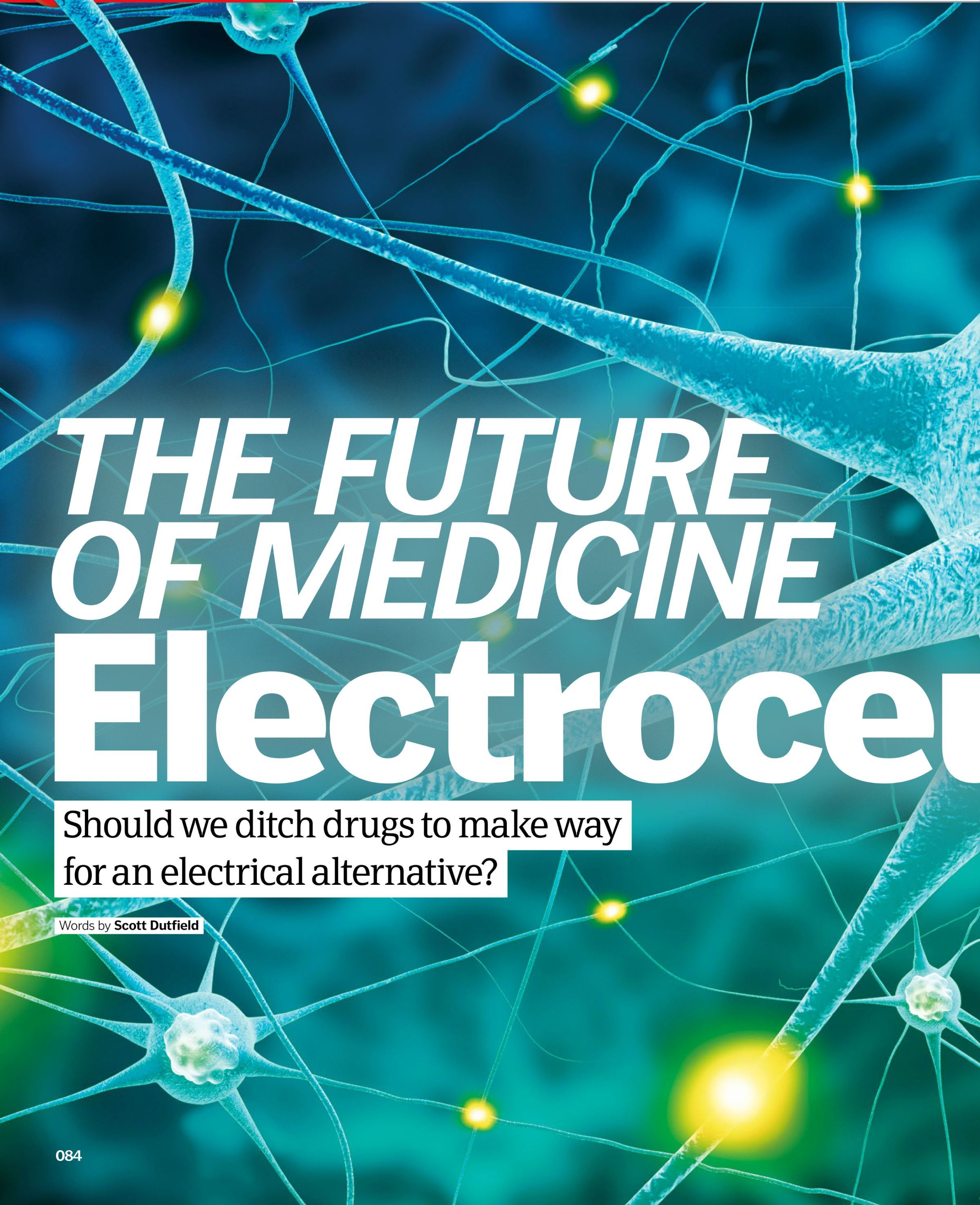
1.2%
Decline in packaging waste recycling or recovery in the UK from 2016 to 2017.

1874
The year in which the UK's first waste incinerator was built.

2kg
The amount of rubbish each person in the US produces every day.

80-85%
Amount of solid mass that an incinerator removes from waste.

267,000m²
Floor space of the waste-to-energy plant set to be opened in Shenzhen, China.



THE FUTURE OF MEDICINE Electroce

Should we ditch drugs to make way for an electrical alternative?

Words by **Scott Dutfield**

U KNOW? *In the future, electroceutical implant devices could be less than 100 nanometres wide [as small as a virus]*

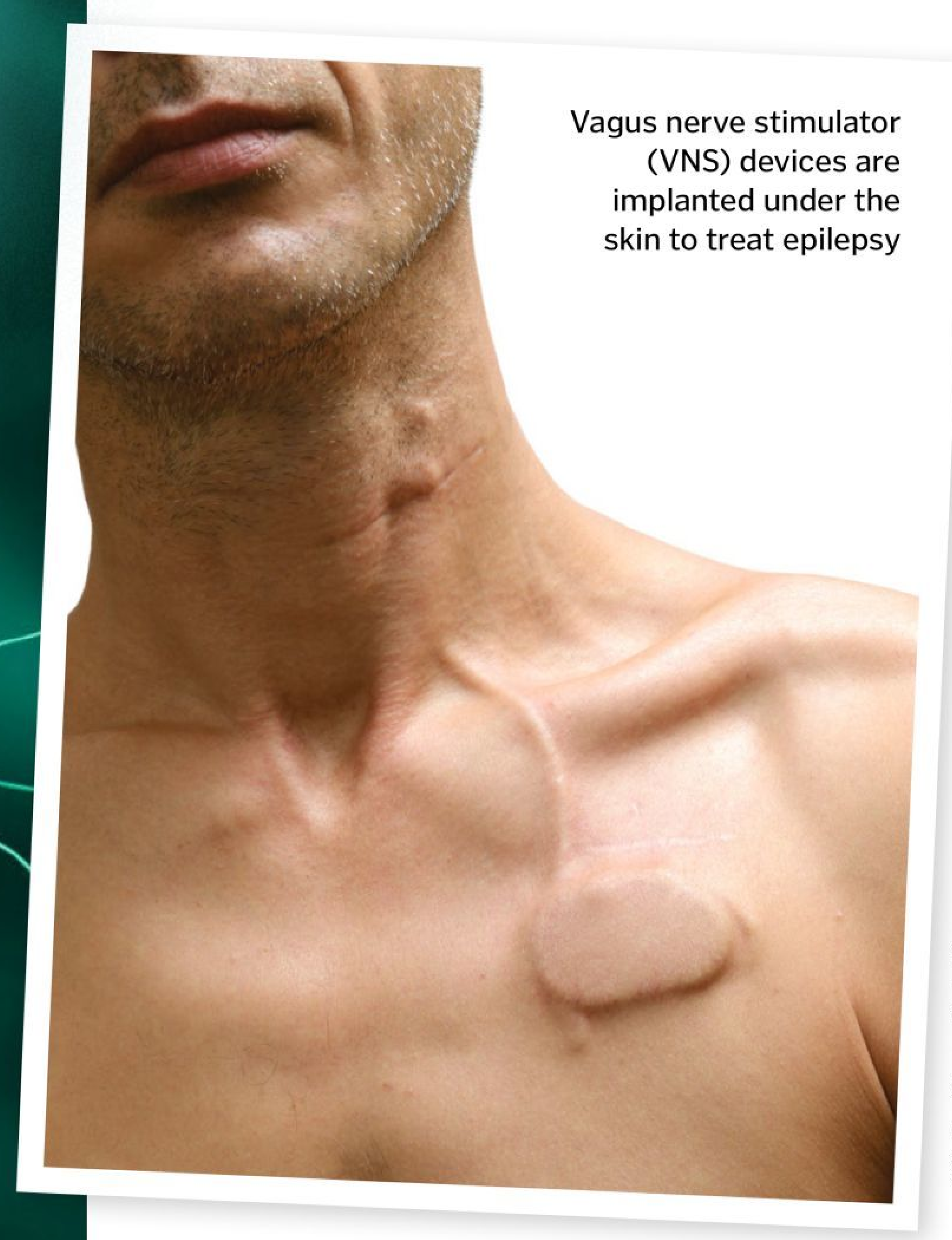
uticals

A great many of us often don't think twice about popping a pill to treat a chronic condition. The most up-to-date data from the European Union suggests around 49 per cent of people within its 28-member countries aged 15 and over use prescribed medicines. However, with the introduction and development of bioelectronic technologies, pills could soon be a thing of the past for some conditions.

Implanted electrical devices that work to repair, replace or restore parts of our bodies have been employed by doctors since the 1950s. The first cardiac pacemaker was implanted in a 43-year-old male back in 1958 to combat his cardiac arrhythmia. Since then devices have been created to restore senses such as hearing and sight and regulate insulin for those suffering from diabetes. However, in recent years 'electroceutical' devices have been making waves as a treatment for chronic conditions.

Fundamentally, the principle of electroceuticals is to emit a low-energy electrical pulse to stimulate different nerves in the body to aid the reduction of symptoms for an array of physical conditions such as epilepsy and rheumatoid arthritis. Recent investigations into externally worn devices have even suggested that they might be a treatment solution for mental health conditions such as depression and anxiety, an incredibly exciting possibility.

One of the biggest downfalls of chemical medication are the potential side-effects they can cause. These side-effects mostly occur due to pharmaceuticals affecting not only the intended target but several organs when they enter the body. Electroceutical treatments offer a more accurate approach as they can focus on



Vagus nerve stimulator (VNS) devices are implanted under the skin to treat epilepsy

particular nerves connected to specific organs, limiting the number of side-effects. For example, one of the most widespread uses of electroceuticals is treating epilepsy with a vagus nerve stimulation (VNS) device. Epilepsy is a condition whereby nerves 'fire off' abnormally when sending signals to different parts of the body, resulting in seizures of varying degrees. The condition affects more than 500,000 people in the UK alone. VNS devices are able to help manage these symptoms through artificial electrical stimulation.

Implanted beneath the skin and hooked onto the vagus nerve at the neck, a generator, which resembles that of a pacemaker, creates electrical pulses that feed through a lead to the nerve at regular intervals. This stimulation regulates the electrical signals through the vagus nerve into the brain, reducing seizures. Should a seizure occur, or even a warning of an oncoming episode, a handheld magnet can be waved over the implant's generator to produce more impulses, preventing or reducing its longevity.

These VNS devices are not a cure for a condition, but they greatly relieve the symptoms. The same technology has also been used to treat those with rheumatoid arthritis, a long-term autoimmune disease that causes inflammation at the joints. A VNS device can send electrical impulses along the splenic nerve to stimulate the spleen, thereby reducing its immune response and any inflammation.

The potential for electroceuticals to become commonplace treatments is vast, but finding the right nerve circuitry can be a tricky task. There are 12 pairs of cranial nerves and around 86 billion neurons in the brain alone, each delivering electrical messages through nerves around the body.

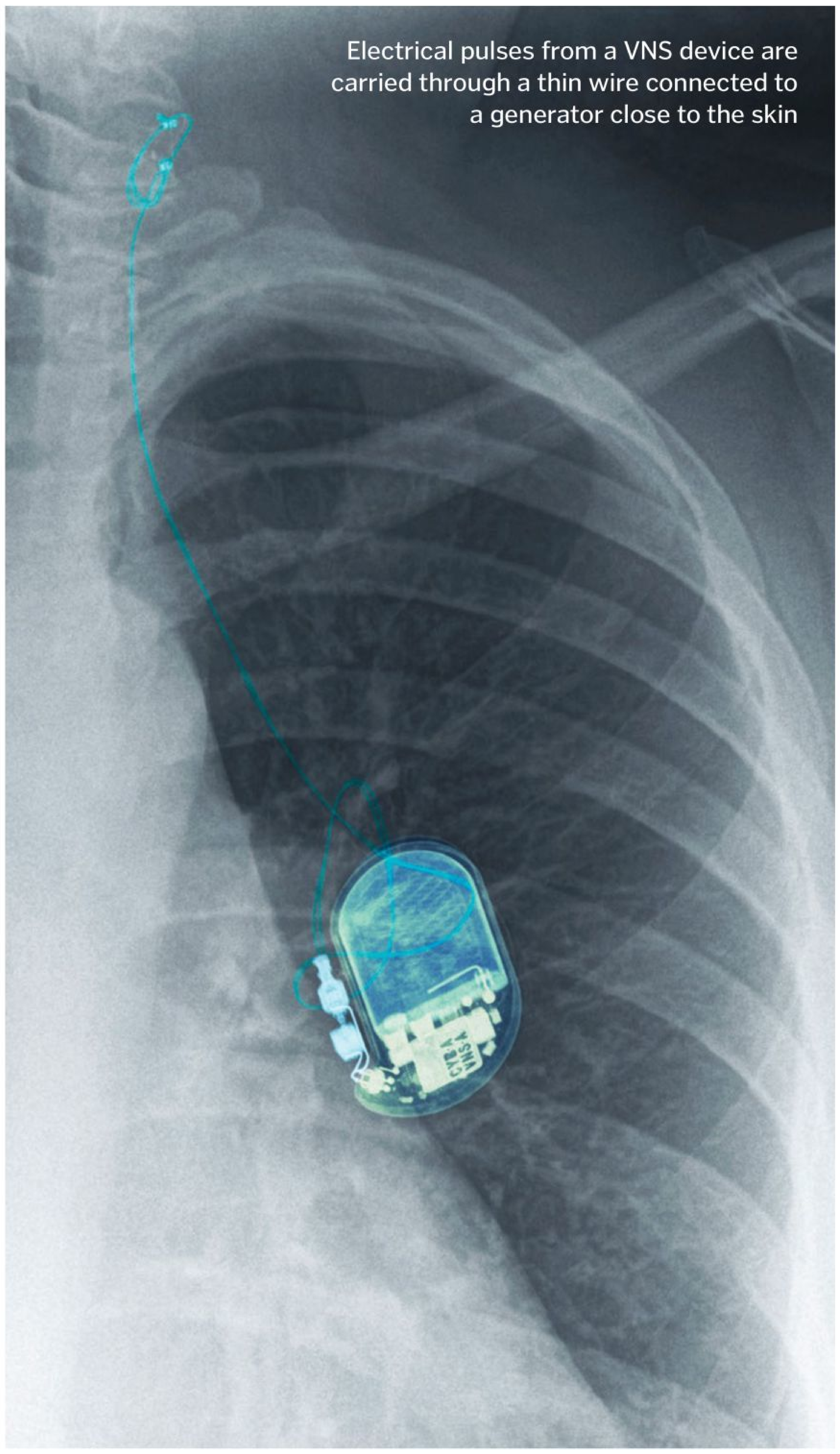
In order to use nerves as a method of treatment, scientists must first locate which nerve carries which message and to where around the body. Brain mapping is a way of creating a road map of the mind to reveal all the avenues through the body. There are several methods currently used to map the brain, one of which is electromyography, which measures the electrical activity in the brain through electrodes placed around the head. However, each of our brains is wired differently, with the exception of major nerves such as the vagus nerve. Therefore it is difficult to create universal electroceuticals, and thus far a complete map of the brain's complex network of neurons is yet to be visualised.

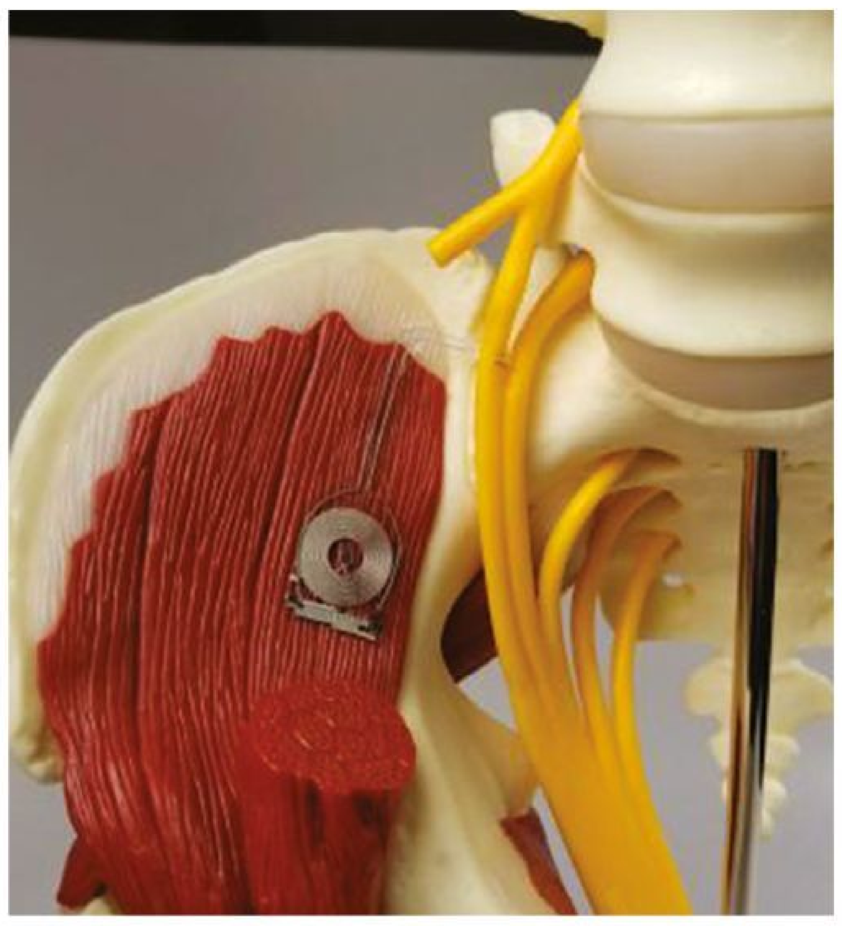
"Electroceutical devices have been making waves as a treatment for chronic conditions"

Though VNS devices seem to hold the monopoly on bioelectronics, recent discoveries are shedding light on the potential for electroceuticals to repair physical damage within the body too. Earlier this year researchers at the Northwestern University and the University of Washington, US, created an implantable wireless device that speeds up the regeneration of damaged nerves.

The device (trialled on rats) emits regular pulses of electricity to damaged sciatic nerves to accelerate nerve growth and enhance muscle control and recovery. Consisting of a thin disc that wraps around nerves, the stimulator is activated wirelessly by a transmitter outside the body. This technology is designed to only work for a specific amount of time during the healing process. Engineers use materials that allow it to biodegrade and be absorbed into the body, preventing another extraction surgery.

Of course, electroceuticals are not the answer to all of our medical problems; bacterial diseases, for example, cannot be treated using these electrifying methods. Electroceutical technology is still in its medical infancy in terms of its general use, and its long-term effects have yet to be determined.


Electrical pulses from a VNS device are carried through a thin wire connected to a generator close to the skin


New devices built to repair nerves will dissolve once the healing is completed


Electromyography uses electrodes to map the brain's neural pathways

Wearable tech

Meet the man behind Modius – the electro-stimulation headset that tricks the brain into thinking you're working out

Dr Jason McKeown is the CEO and co-founder of Modius Health. Here he explains the science behind their new headset and what the future may hold for wearable electronic medicine.

How does Modius stimulate weight loss?
The hypothalamus controls all elements of metabolism, so that's your metabolic rate, core temperature, your appetite even and all of your hormone profile. Your vestibular nerve connects to that, so we used electricity to stimulate the nerve, similar to the way implants do. We believe that your vestibular nerve picks up physical activity, so it's almost a reference point to how active you are. Say you're a bear hibernating; there is zero physical activity, so your vestibular input is zero because you're just lying there, sleeping. So the metabolism shifts slightly to store fat. It's a very old evolutionary thing that guides metabolism to how physically active we are. So basically, we kind of hack that connection to some degree and activate it over and over again using electrical stimulation, and that's how we developed this headset that you can wear for an hour to repeatedly stimulate that part of the brain.

Why doesn't this form of stimulation affect other brain functions?
The vestibular nerve itself only has projections into the areas [of the hypothalamus] that physical activity has any reference to. It's almost like a filter that works by filtering areas that are only relevant for things that connect with physical activity.

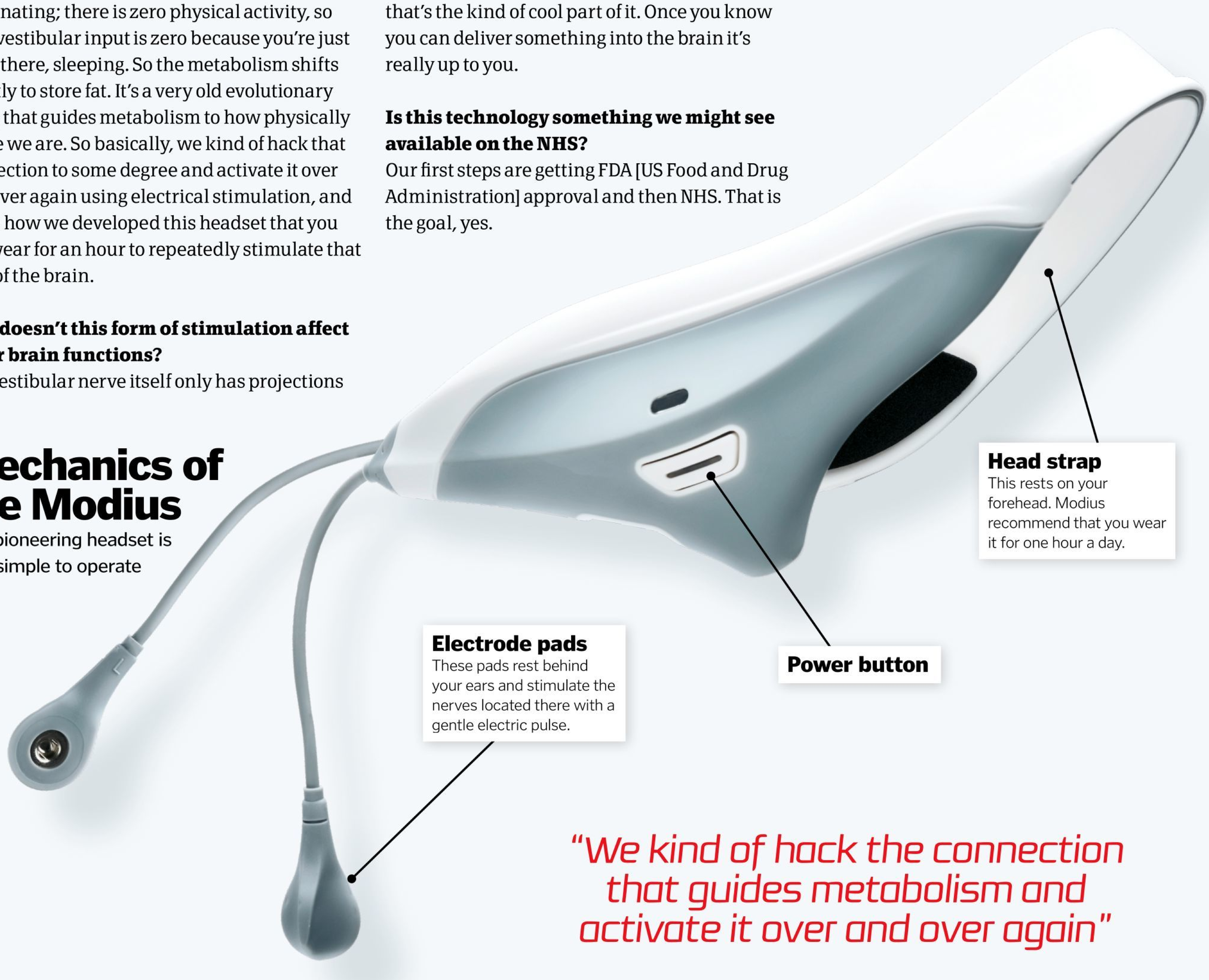
What is the future of Modius Health and wearable bioelectronics?
What we can do isn't limited to weight loss. That just happened to be the first thing we looked at. So we are actually looking in the mental health space, at anxiety and depression also. We have also started trials in migraines and epilepsy. People think we are just a weight loss company, but the technology is actually a delivery method. It delivers stuff to the deep part of the brain, that's the kind of cool part of it. Once you know you can deliver something into the brain it's really up to you.

Is this technology something we might see available on the NHS?
Our first steps are getting FDA [US Food and Drug Administration] approval and then NHS. That is the goal, yes.

Dr McKeown founded the Belfast-based company Modius Health in 2013

Mechanics of the Modius

This pioneering headset is very simple to operate



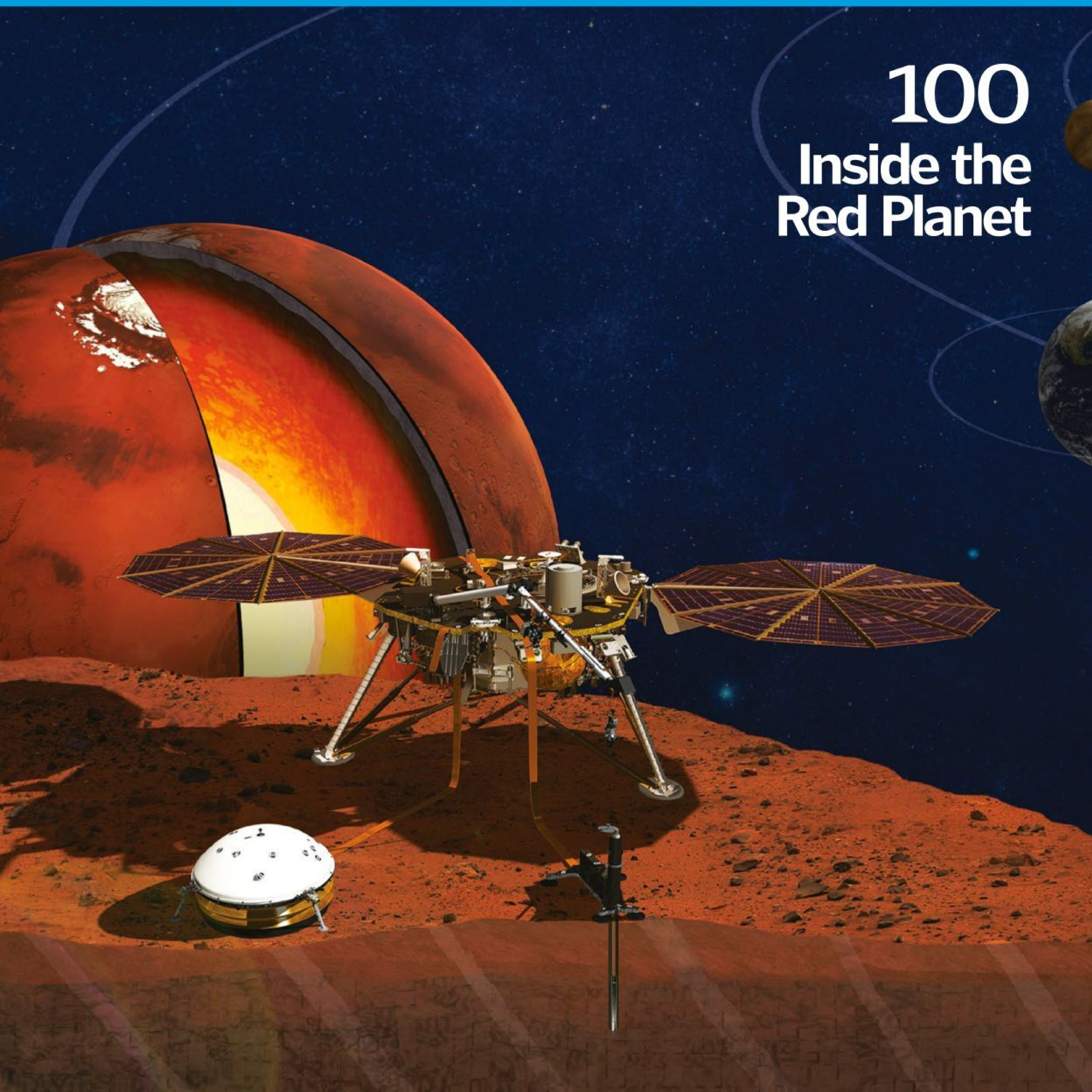
"We kind of hack the connection that guides metabolism and activate it over and over again"

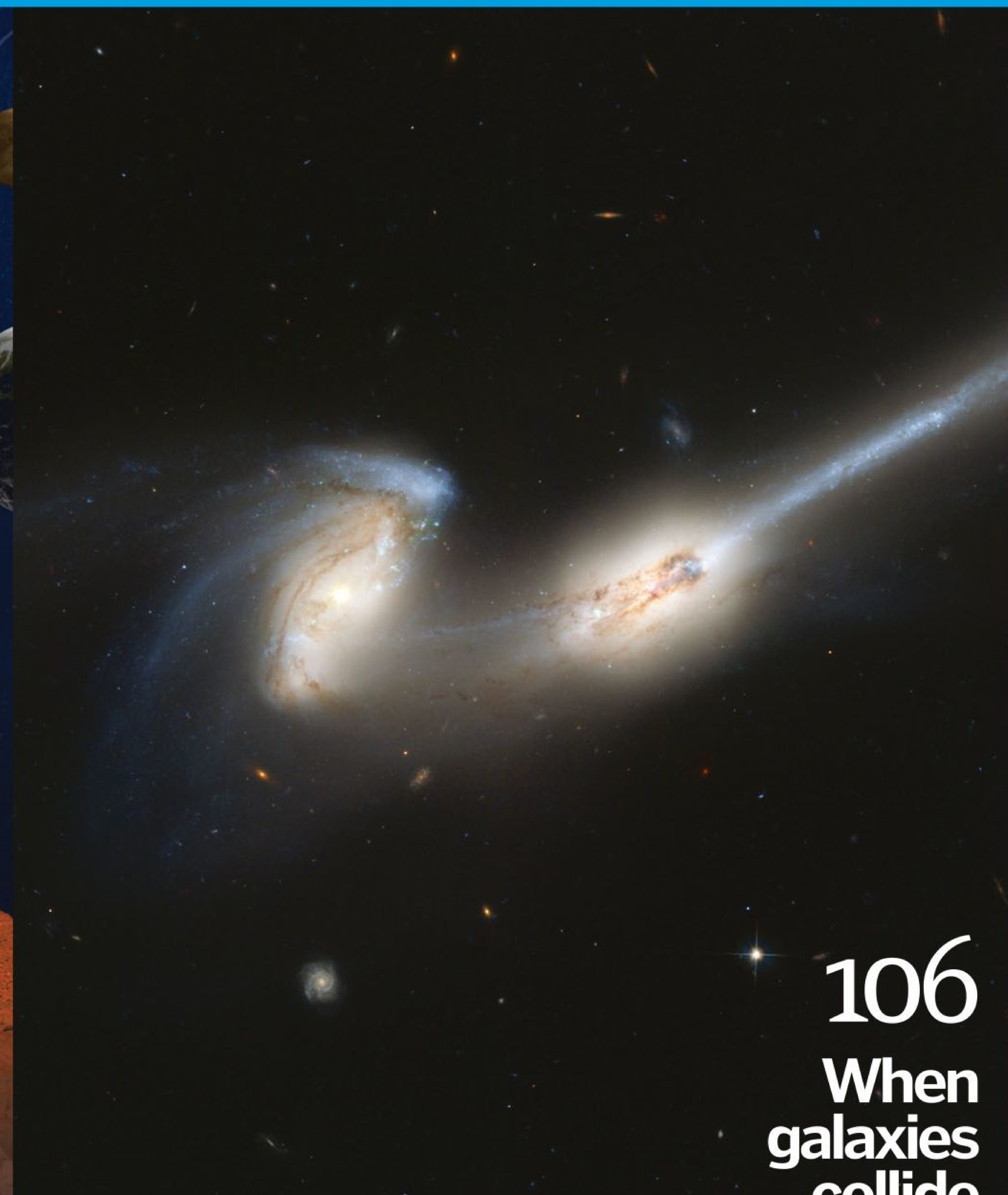
SPACE

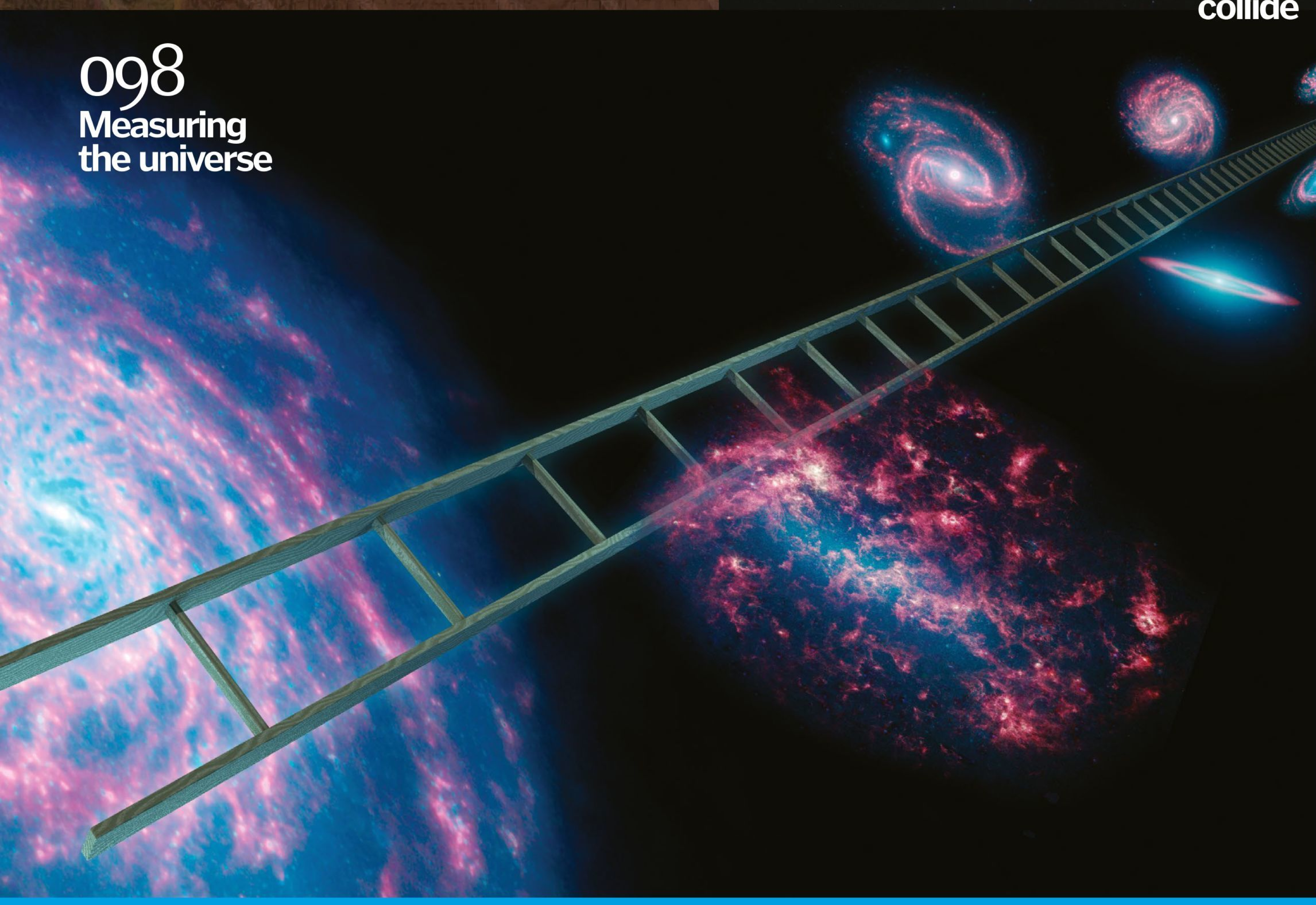

COLLINS
ALDRIN
ARMSTRONG
NASA
090
Secrets of Apollo 11


107
Redshift and blueshift

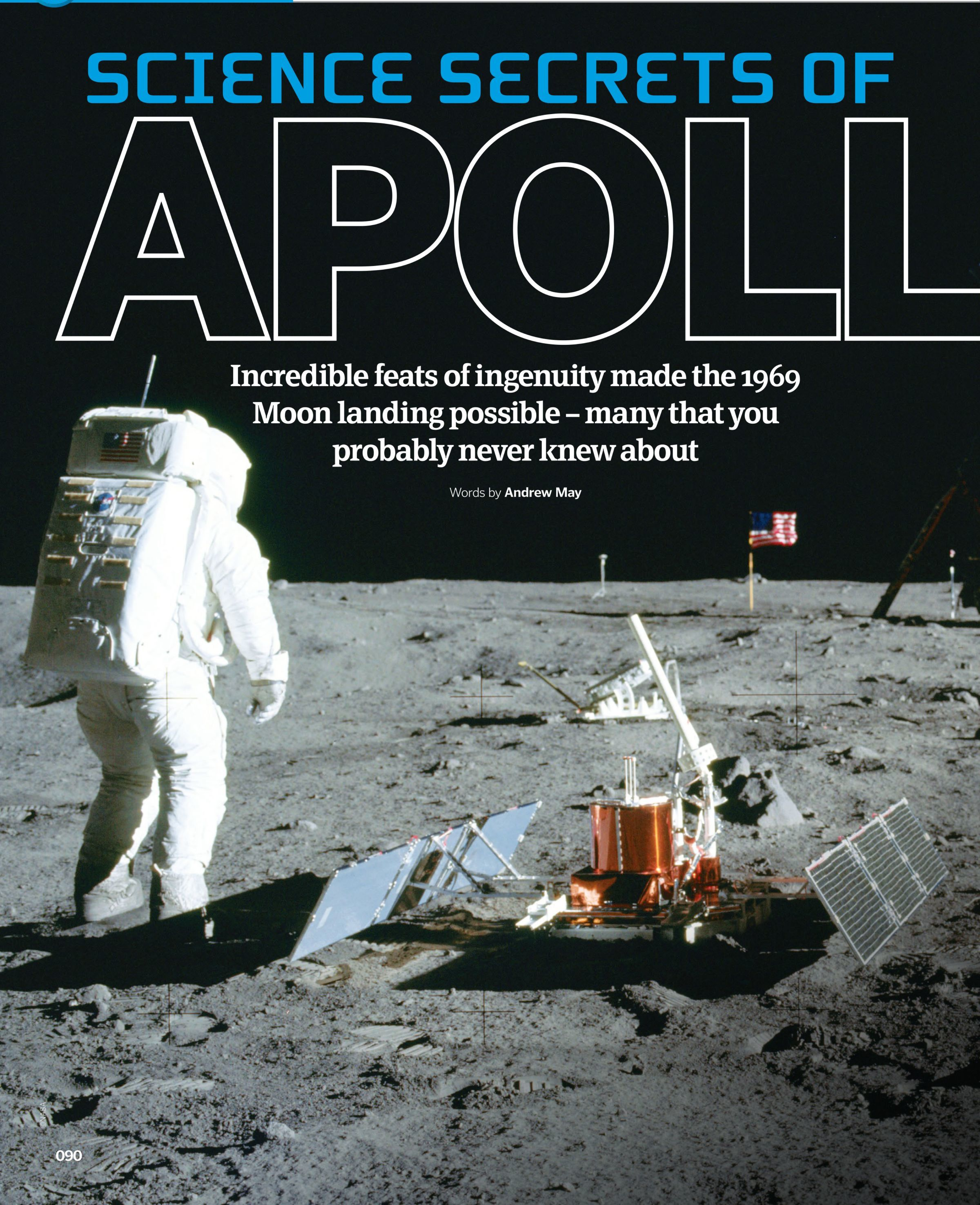

108
Impact Earth





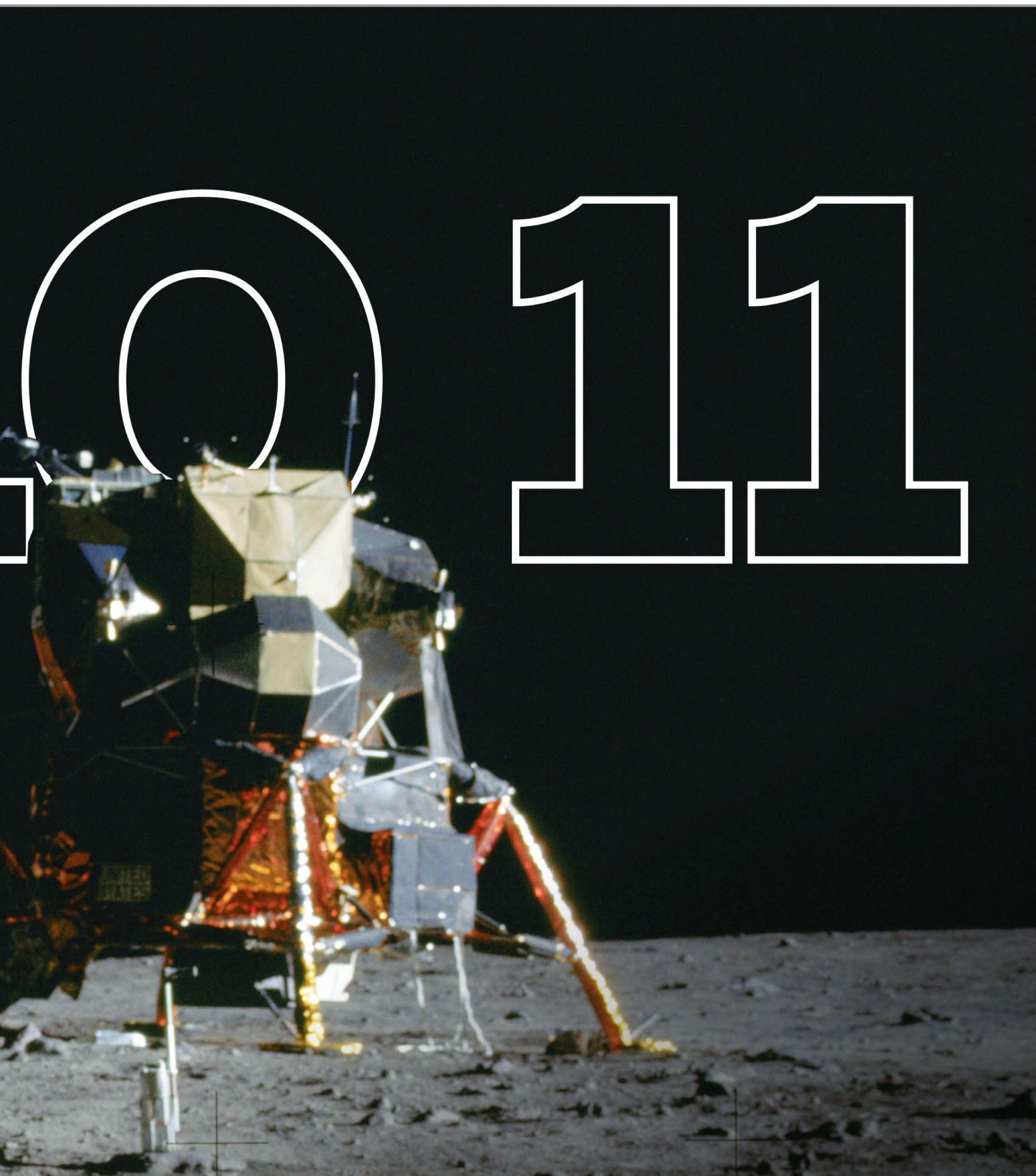


SCIENCE SECRETS OF APOLL



Incredible feats of ingenuity made the 1969 Moon landing possible – many that you probably never knew about

Words by **Andrew May**



Fifty years ago last July, Apollo 11 carried three astronauts – commander Neil Armstrong, Command Module pilot Michael Collins and Lunar Module pilot Edwin 'Buzz' Aldrin – all the way to the Moon. Once there, Armstrong and Aldrin went down to the surface for a history-making moonwalk, while Collins stayed in lunar orbit. Then they returned to Earth, splashing down in the Pacific some eight days after they left the planet.

Even from today's perspective, the Moon landing was an astonishing achievement, and in 1969 it pushed the limits of what was technologically possible. Yet the science behind it was 300 years old, going all the way back to Isaac Newton's law of gravity, first formulated in the 1660s. That may sound counterintuitive, because gravity is what holds us to the surface of the Earth. But if you toss a ball up in the air, it travels higher and higher as you launch it with increasing speed. Newton realised the same trend continues out in space. The faster something leaves Earth, the further it travels before coming back. Give it enough speed – sideways as well as up – and it will go into orbit. Even more speed, and it can reach the Moon.

The first humans to reach the Moon – going round it, rather than landing – were the crew of Apollo 8 in December 1968. They understood the science as well as anyone. As one of them, William 'Bill' Anders, said on the journey home, "I think Isaac Newton is doing most of the driving right now." That's not Newton himself, of course, but his law of gravity. It's the reason spacecraft don't need to run their engines all the time, just in short 'burns' to get up to the right speed, and then gravity does the rest.

"I think Isaac Newton is doing most of the driving right now"

Using the world's biggest rocket

The key to getting a spacecraft to the Moon is giving it enough speed – around 11 kilometres per second – to carry it all the way there before it falls back to Earth. The Apollo spacecraft weighed close to 50 tons, so accelerating all that mass to the necessary speed required a lot of energy. The solution: the 111-metre-tall, three-stage Saturn V. Designed by the German-American rocket scientist Wernher von Braun, it remains to this day the largest, most powerful space launcher that has ever flown.

©NASA

The Saturn V's main engines tower over its designer, Wernher von Braun

Launching precisely on time

One of the most dramatic features of any space mission is the pre-launch countdown. But it's not there simply to add edge-of-the-seat excitement for people watching – it's to make sure all the necessary tests and preparations are done at the right moment and in the correct order. It's also important to hit the launch window – a short period of time within which the launch has to take place. Missing it means postponing the launch until another day.

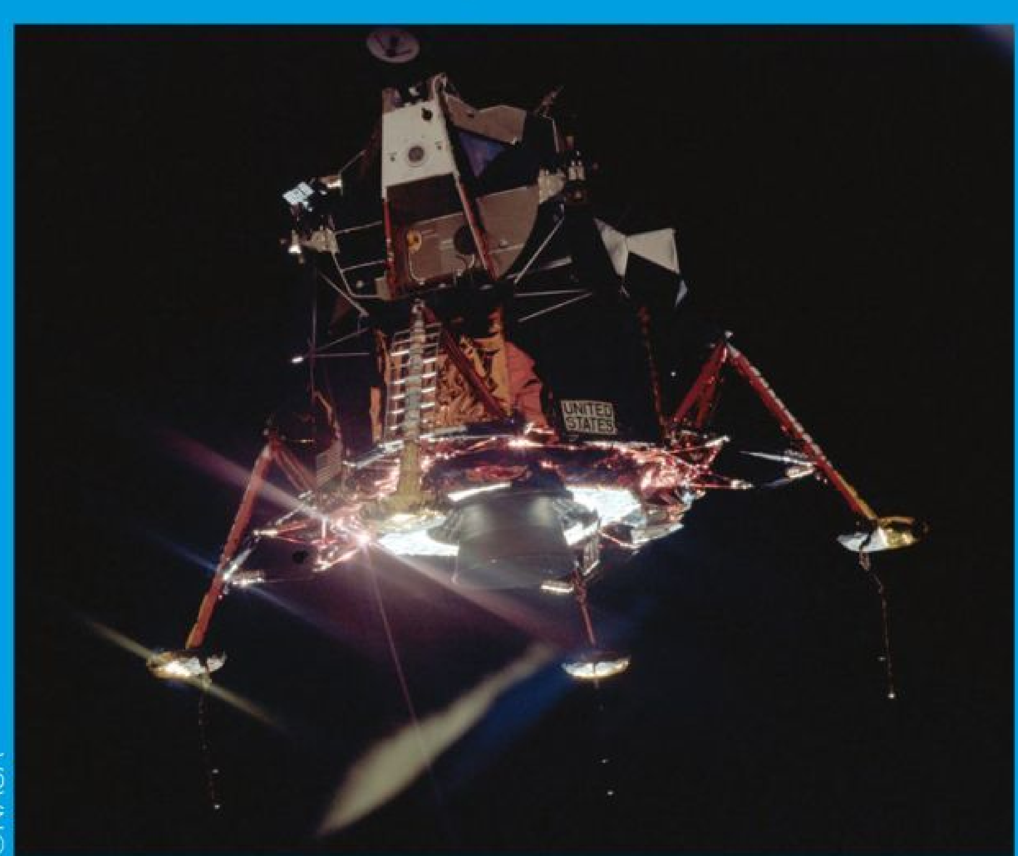
Once again, the launch window is all about science. The Earth is rotating and the Moon is moving in orbit around it, so everything has to line up just right for the launch to be successful. There are practical considerations too, such as making sure there will be a good line of communications between the spacecraft and the ground at critical moments.

Apollo 11 during a night-time countdown test a few days before launch

©NASA

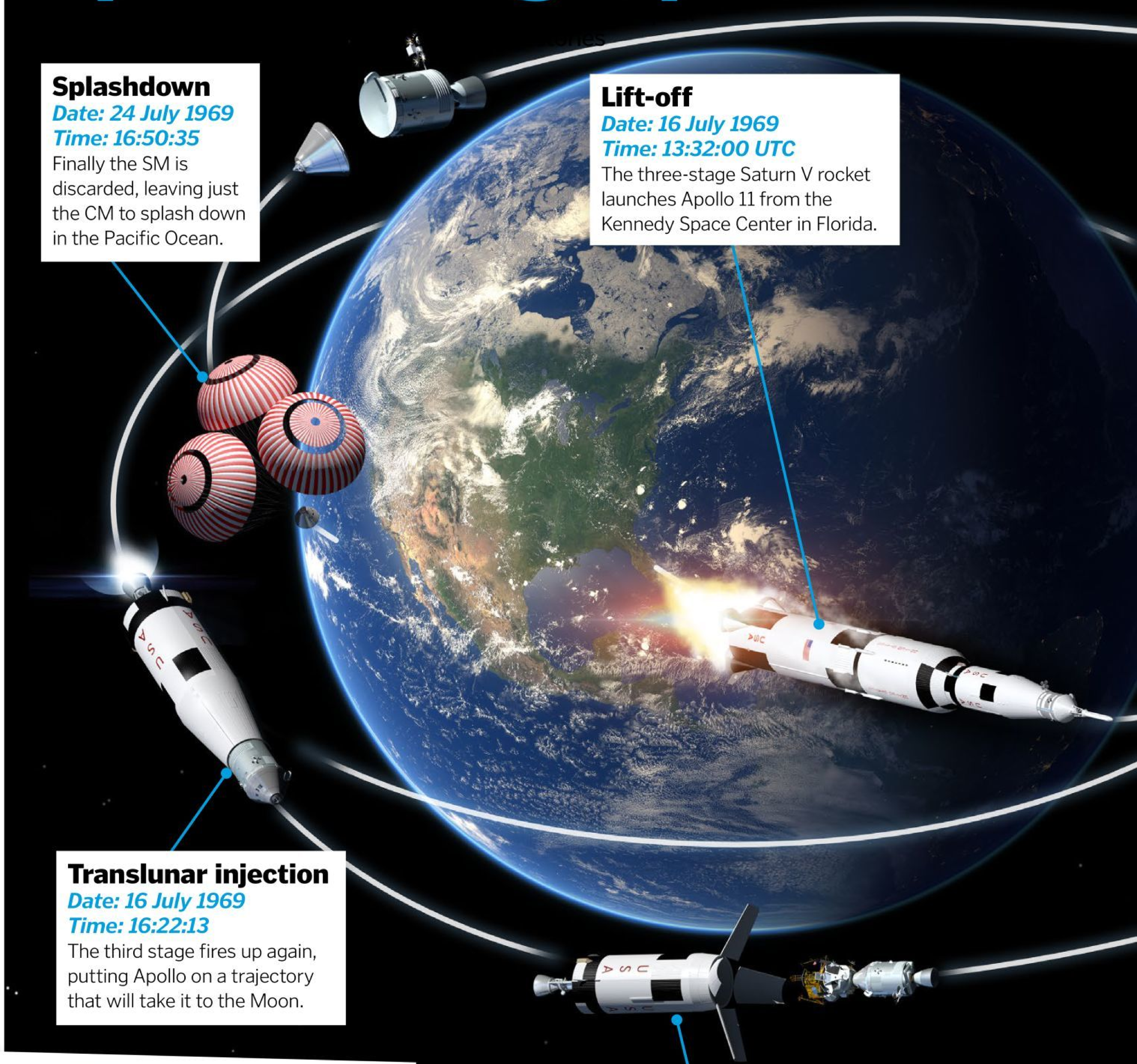
Combining two spaceships into one

When NASA first conceived the Apollo project at the start of the 1960s, it was assumed the whole spacecraft would land on the Moon and then take off again to return to Earth. But that's really not very efficient. The amount of fuel a rocket needs increases with mass, and if you do things this way you're lifting more mass off the Moon than you need to. You can save fuel by going down to the surface in a separate landing vehicle specially designed for that task. So Apollo effectively became two spacecraft in one: the Command Module (CM) to get to and from the Moon, and the Lunar Module (LM) for the landing itself.



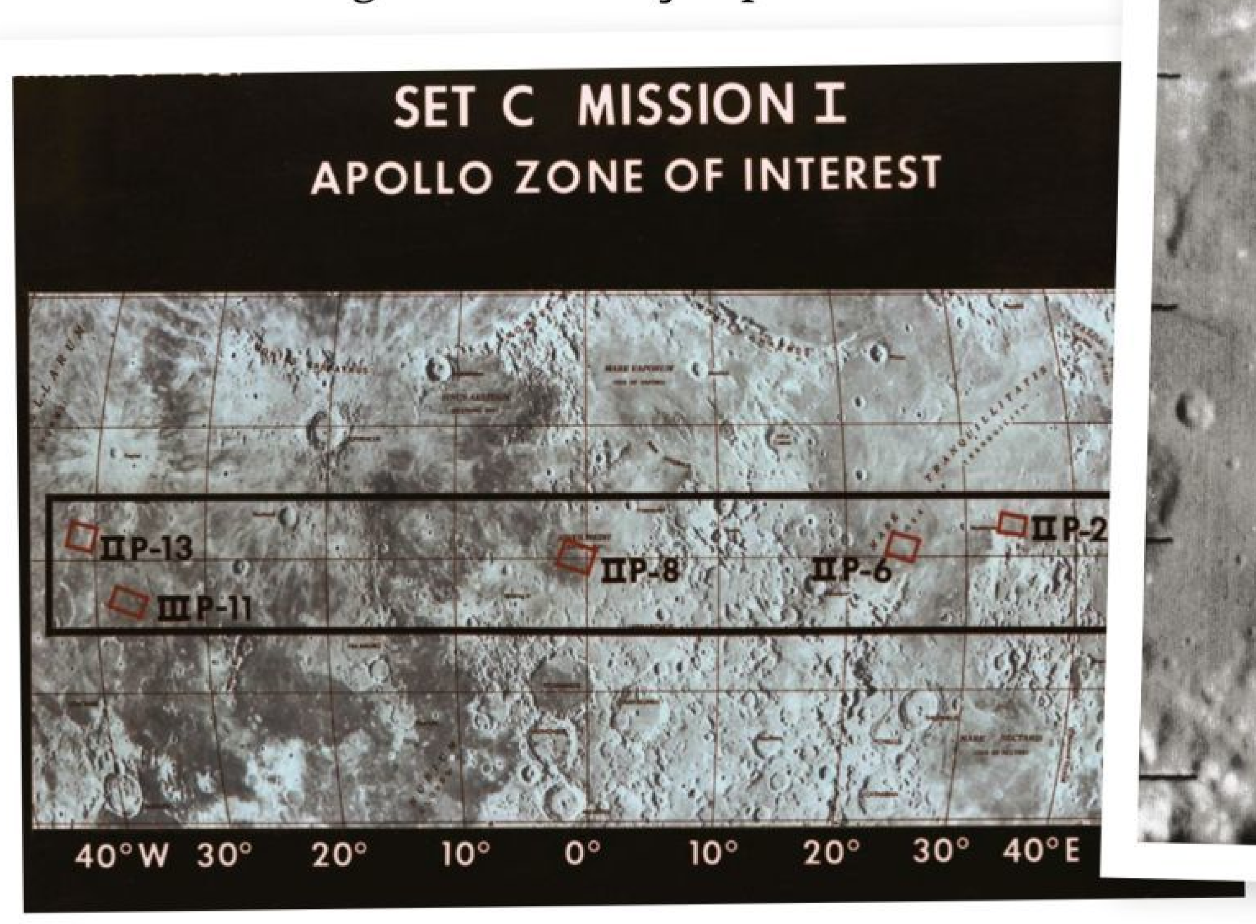
The Lunar Module starts its descent to the Moon, as photographed by Collins in the CM

Apollo 11's flight path



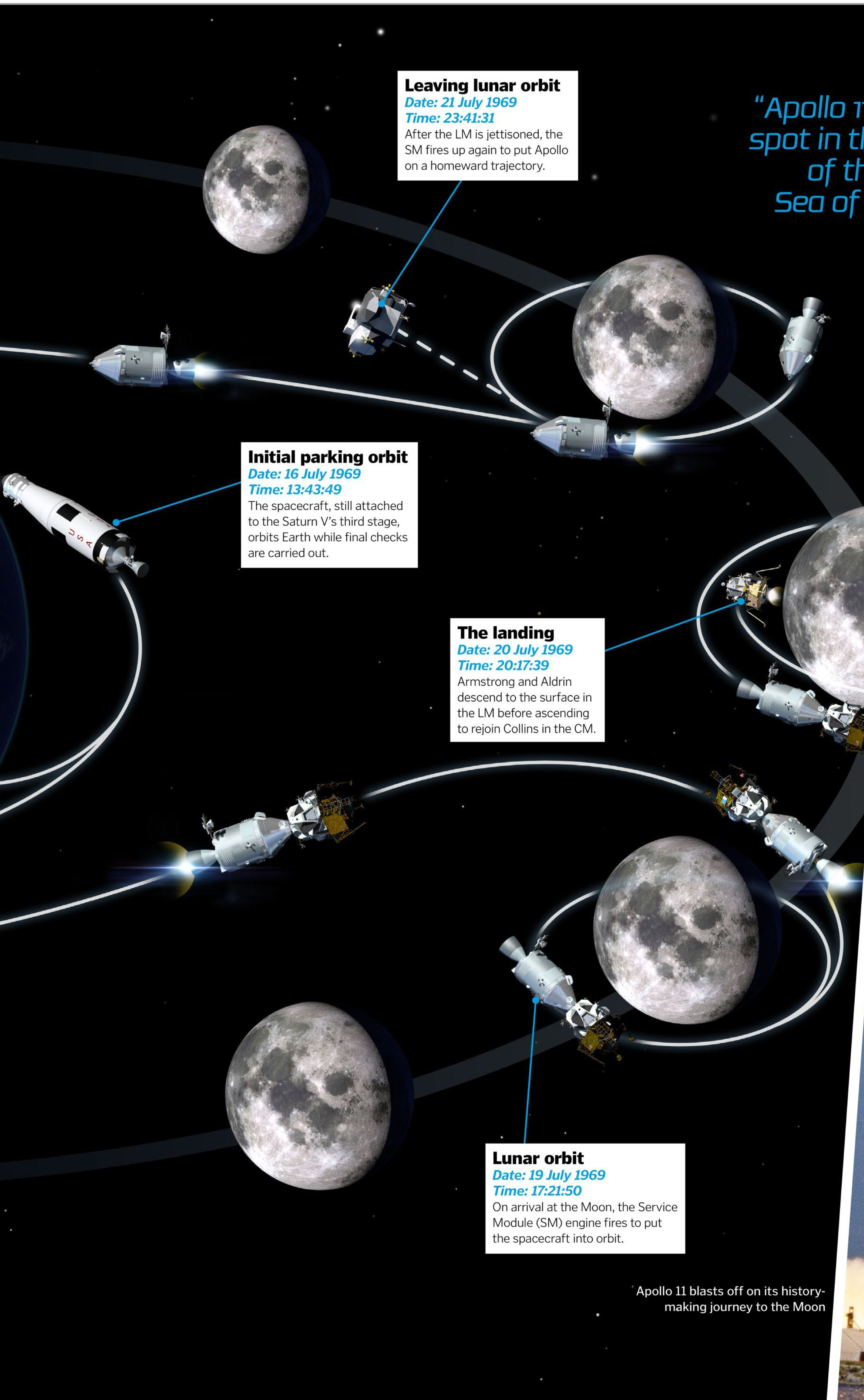
Choosing the right landing site

Apollo 11 headed for a spot in the southwest of the Moon's Sea of Tranquillity – a spot now known as 'Tranquillity Base'. NASA put a lot of thought into a suitable site, coming up with a shortlist of five options. These were all close to the lunar equator, as that provided the least risky trajectory for the spacecraft. Other requirements were for flat, relatively uncratered terrain and good visibility during the approach. These factors were assessed using reconnaissance photos taken by unmanned Ranger and Surveyor probes.



Landing options were all near the Moon's equator – IIP-6 is Tranquillity Base

A reconnaissance photo of the area around Tranquillity Base, taken by Ranger 8 in 1965



Leaving lunar orbit
Date: 21 July 1969
Time: 23:41:31
After the LM is jettisoned, the SM fires up again to put Apollo on a homeward trajectory.

"Apollo 11 headed for a spot in the southwest of the Moon's Sea of Tranquillity"

Initial parking orbit
Date: 16 July 1969
Time: 13:43:49
The spacecraft, still attached to the Saturn V's third stage, orbits Earth while final checks are carried out.

The landing
Date: 20 July 1969
Time: 20:17:39
Armstrong and Aldrin descend to the surface in the LM before ascending to rejoin Collins in the CM.

Lunar orbit
Date: 19 July 1969
Time: 17:21:50
On arrival at the Moon, the Service Module (SM) engine fires to put the spacecraft into orbit.

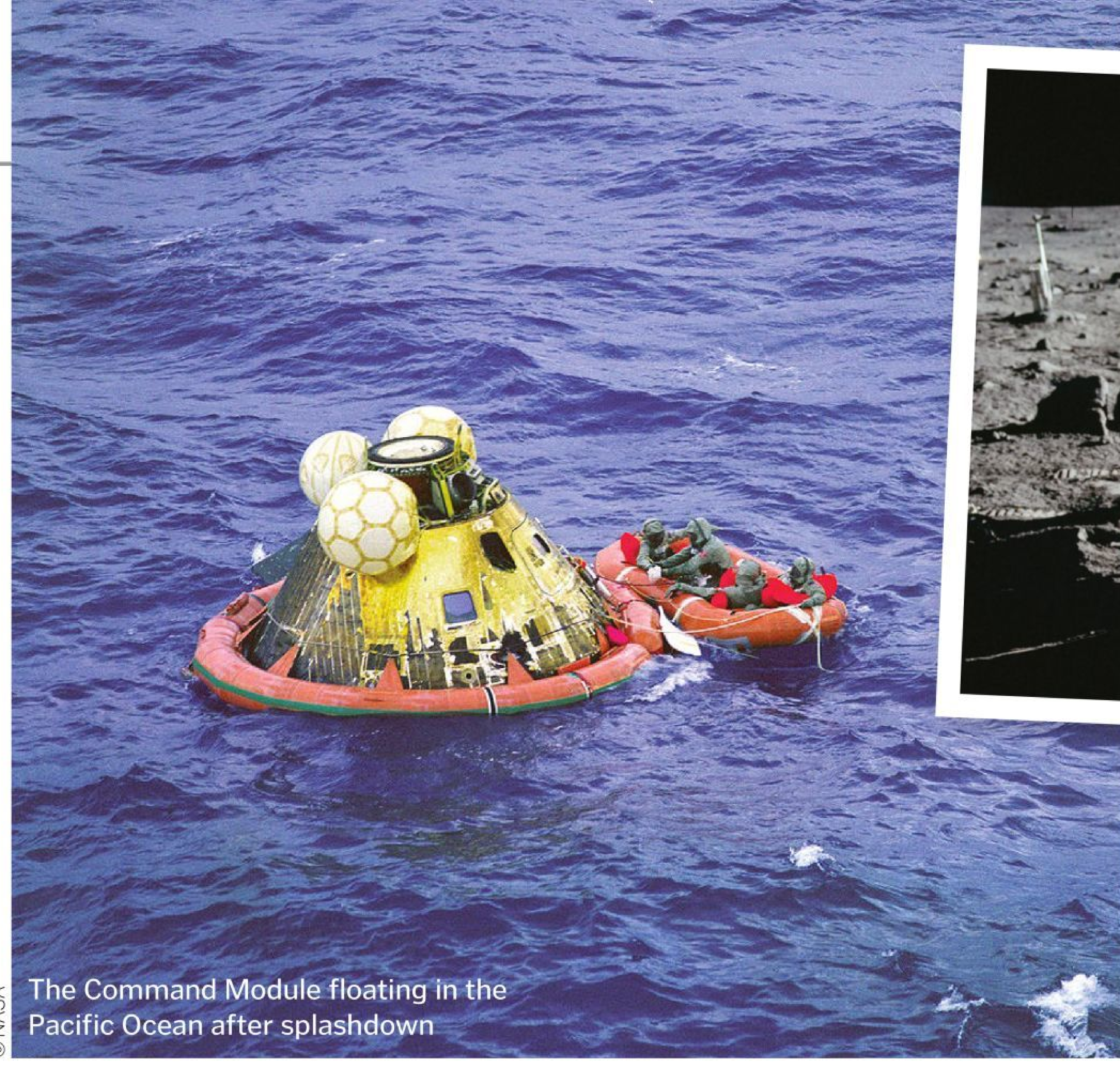
Apollo 11 blasts off on its history-making journey to the Moon

What happened to gravity?

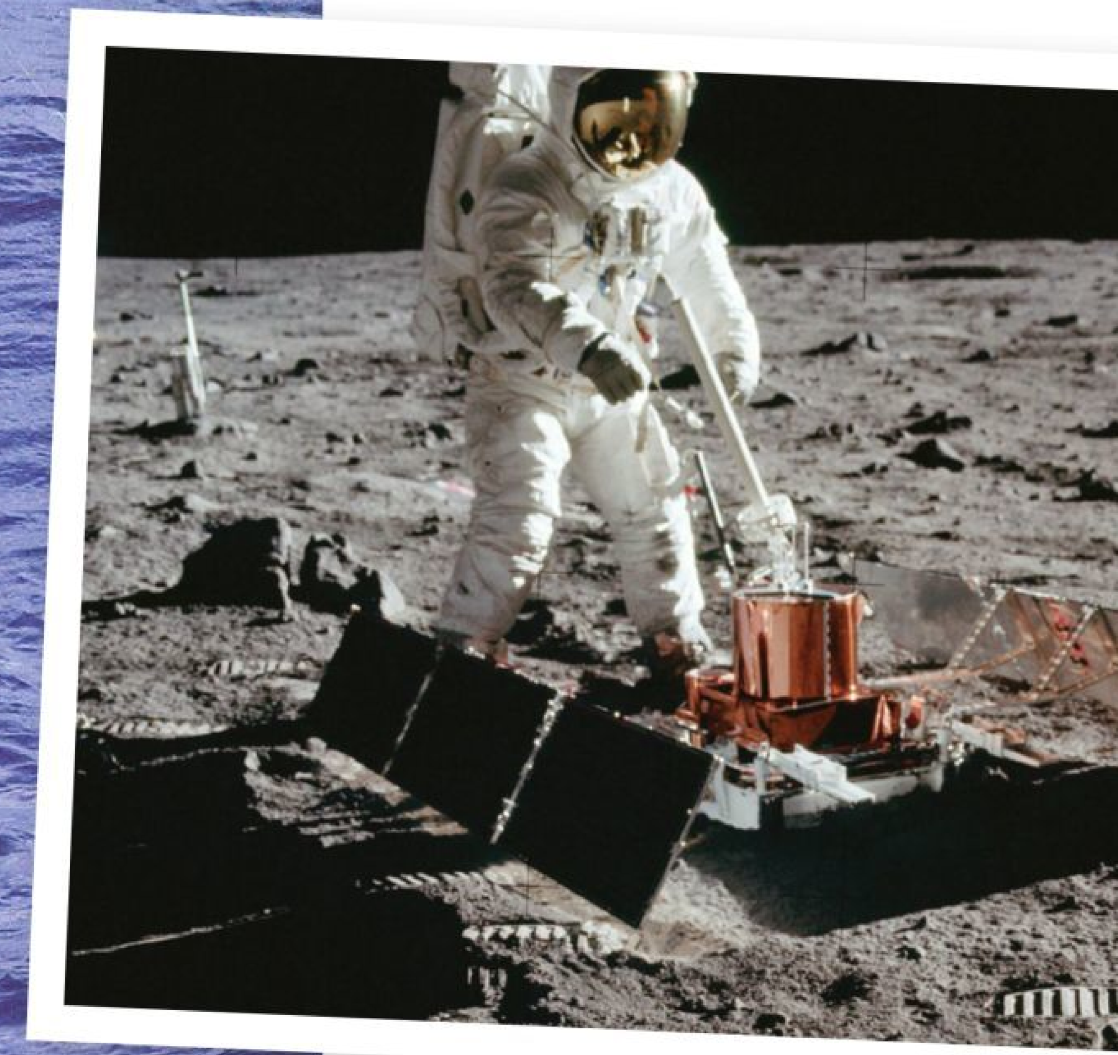
We've seen how gravity is the main driving force in getting to the Moon. Yet one of the most familiar features of spaceflight is the 'zero-g' environment – the way astronauts lose all sensation of weight. How do you reconcile these two facts? As paradoxical as it sounds, the second follows from the first. When an object moves freely in a gravitational field – whether it's falling to Earth, or in orbit around it, or en route to the Moon – it's effectively weightless. If you find that idea difficult, don't worry – Einstein did too. He puzzled over it for years, and when he finally worked it out the result was his famous theory of general relativity.

As the astronauts landed on the Moon, they experienced weight again, but only at a sixth of its strength on Earth. Gravitational fields are generated by mass, and the Moon is much less massive.

Apollo 10 astronauts Thomas Stafford and John Young demonstrate weightlessness



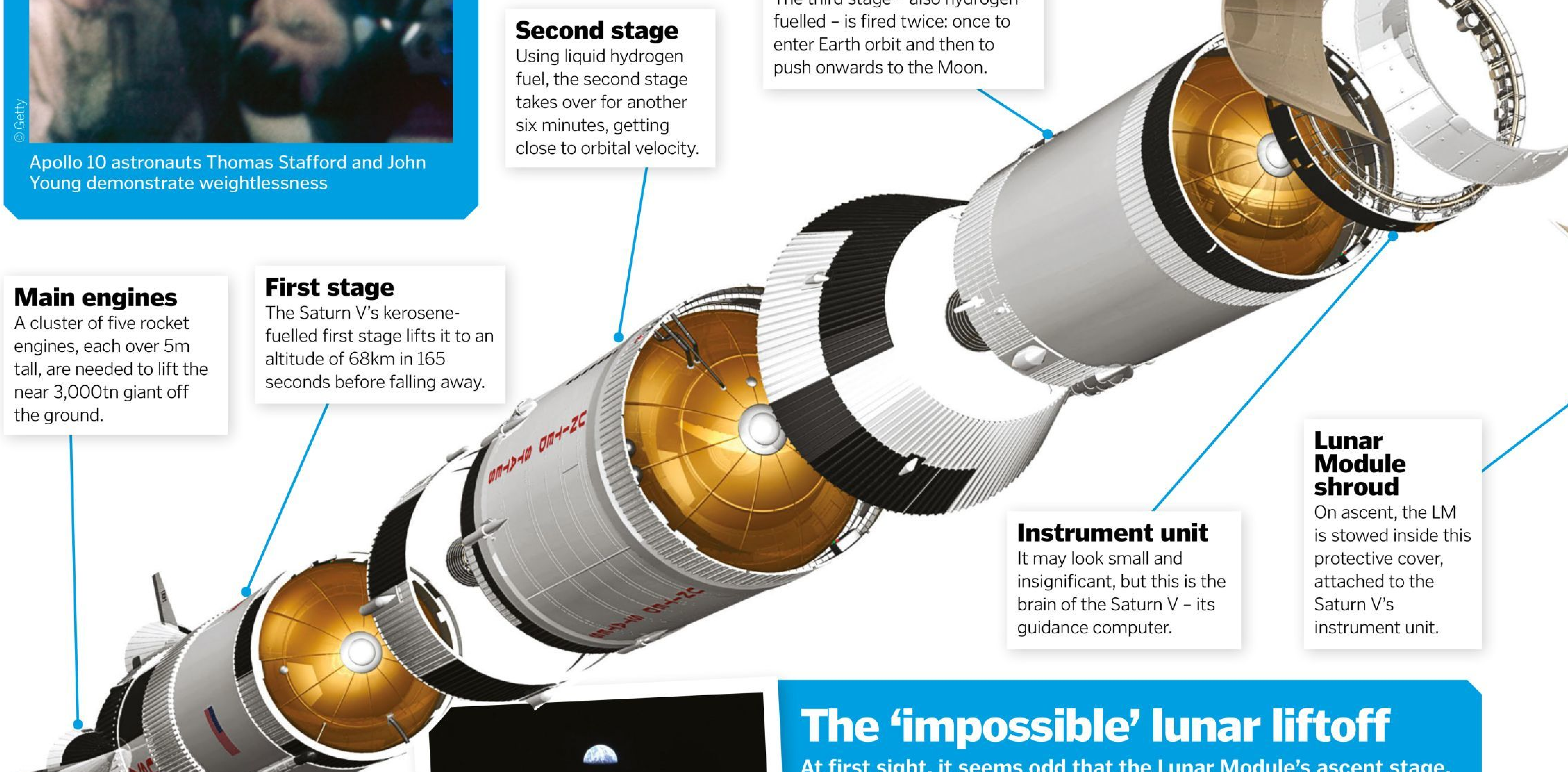
The Command Module floating in the Pacific Ocean after splashdown



The astronauts found time to deploy a few science experiments, such as this seismometer

Anatomy of the Apollo-Saturn V Moon rocket

It was made of around 3 million separate parts: here are some of the most important ones



Third stage
The third stage – also hydrogen-fuelled – is fired twice: once to enter Earth orbit and then to push onwards to the Moon.

Second stage
Using liquid hydrogen fuel, the second stage takes over for another six minutes, getting close to orbital velocity.

Main engines
A cluster of five rocket engines, each over 5m tall, are needed to lift the near 3,000tn giant off the ground.

First stage
The Saturn V's kerosene-fuelled first stage lifts it to an altitude of 68km in 165 seconds before falling away.

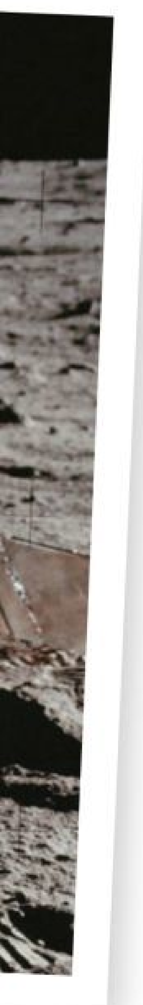
Instrument unit
It may look small and insignificant, but this is the brain of the Saturn V – its guidance computer.

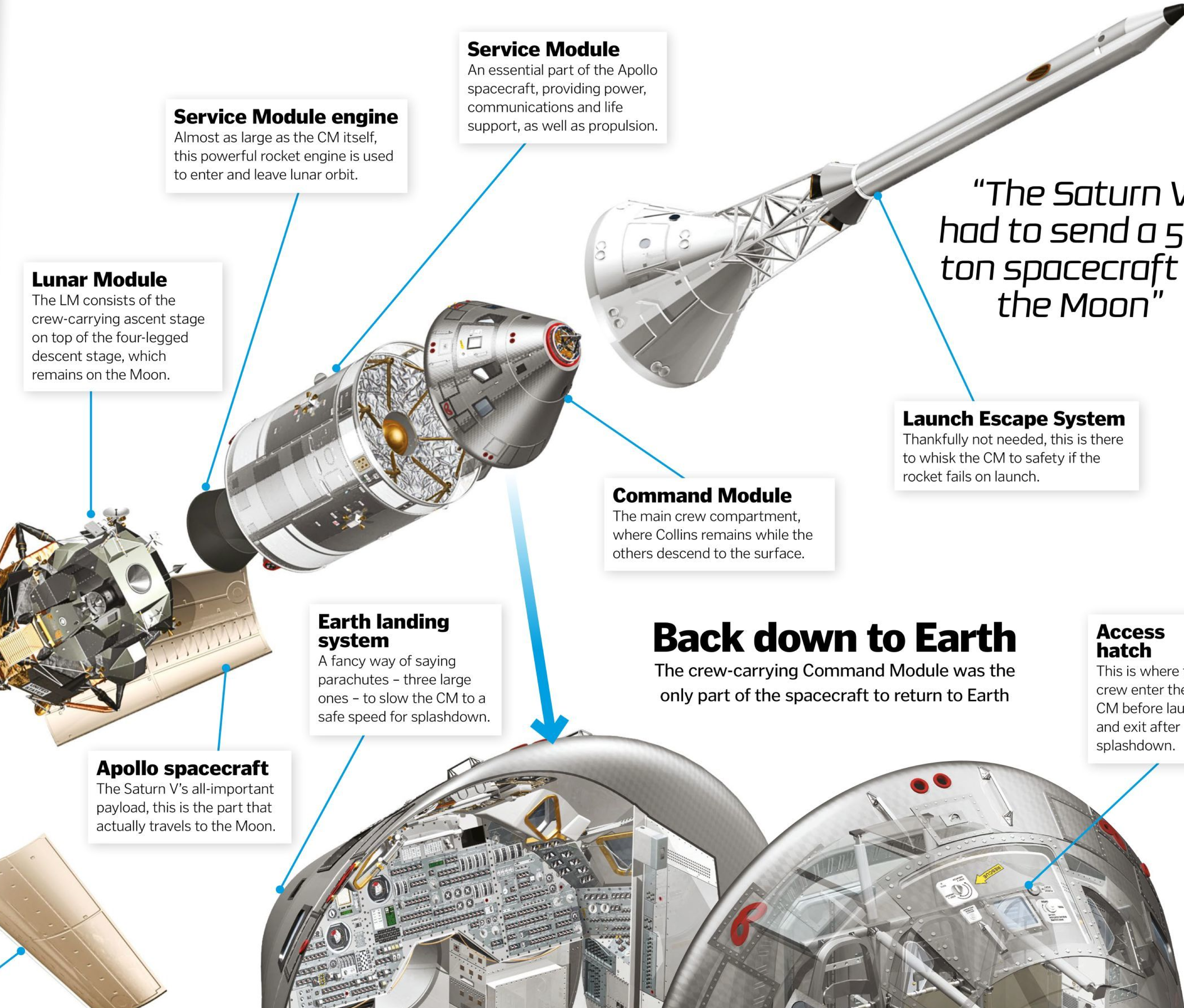
Lunar Module shroud
On ascent, the LM is stowed inside this protective cover, attached to the Saturn V's instrument unit.

The ascent stage of the Lunar Module returning from the Moon's surface

The 'impossible' lunar liftoff

At first sight, it seems odd that the Lunar Module's ascent stage, with just a single small rocket engine, was able to launch two astronauts off the Moon's surface. Didn't it require the enormous Saturn V to get three of them off the Earth? If you look into the physics though, there isn't really any contradiction. The Saturn V had to send a 50-ton spacecraft all the way to the Moon, which calls for a speed of around 11 kilometres per second. In contrast, the LM ascent stage only had to lift itself – less than five tons – while the Moon's weaker gravity meant it could get into lunar orbit with a speed of just 1.6 kilometres per second. So a lot less energy was needed, which is why a smaller rocket did the job.





Service Module
An essential part of the Apollo spacecraft, providing power, communications and life support, as well as propulsion.

Service Module engine
Almost as large as the CM itself, this powerful rocket engine is used to enter and leave lunar orbit.

Lunar Module
The LM consists of the crew-carrying ascent stage on top of the four-legged descent stage, which remains on the Moon.

"The Saturn V had to send a 50-ton spacecraft to the Moon"

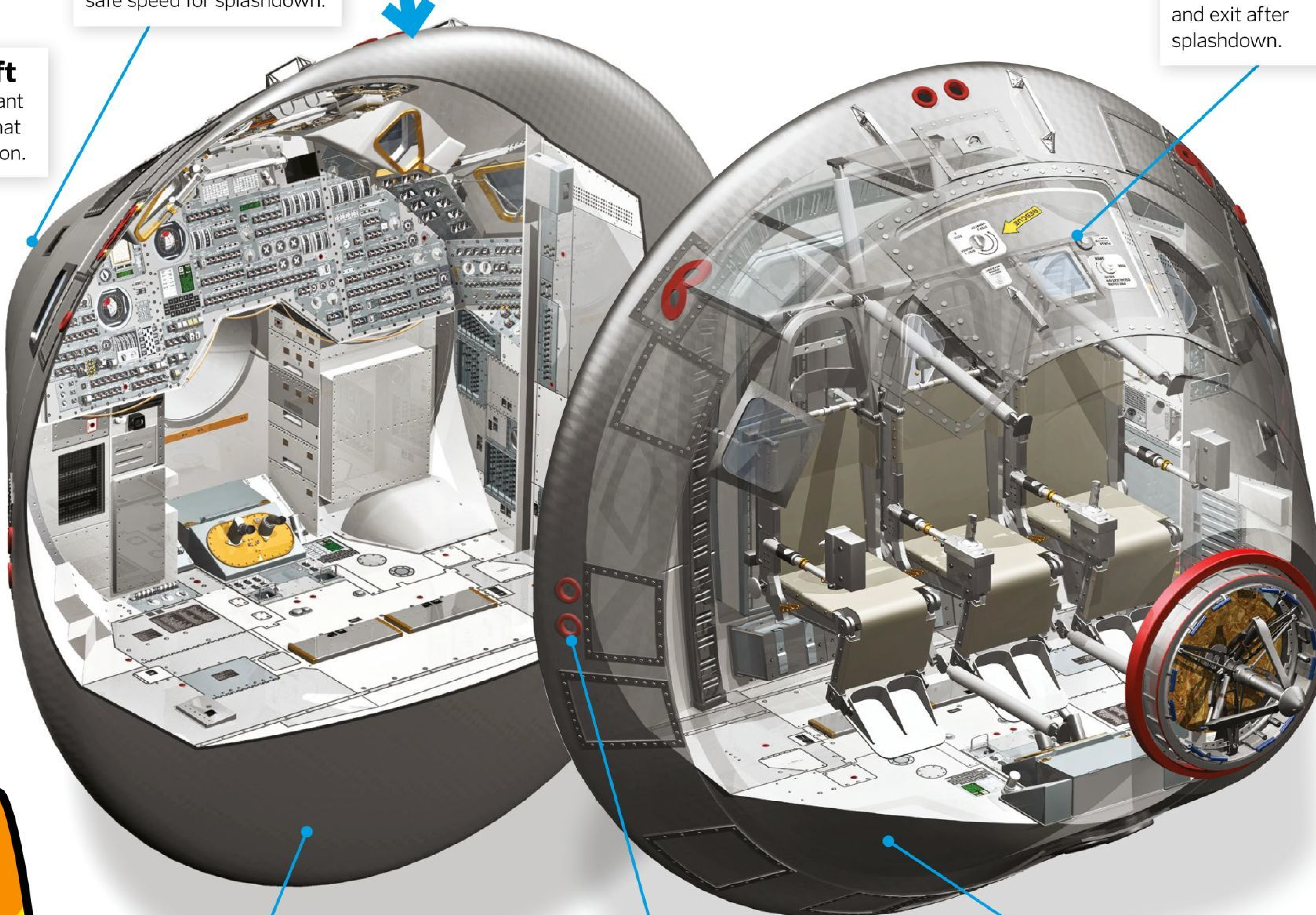
Launch Escape System
Thankfully not needed, this is there to whisk the CM to safety if the rocket fails on launch.

Command Module
The main crew compartment, where Collins remains while the others descend to the surface.

Apollo spacecraft
The Saturn V's all-important payload, this is the part that actually travels to the Moon.

Back down to Earth

The crew-carrying Command Module was the only part of the spacecraft to return to Earth



Earth landing system
A fancy way of saying parachutes – three large ones – to slow the CM to a safe speed for splashdown.

Access hatch
This is where the crew enter the CM before launch and exit after splashdown.

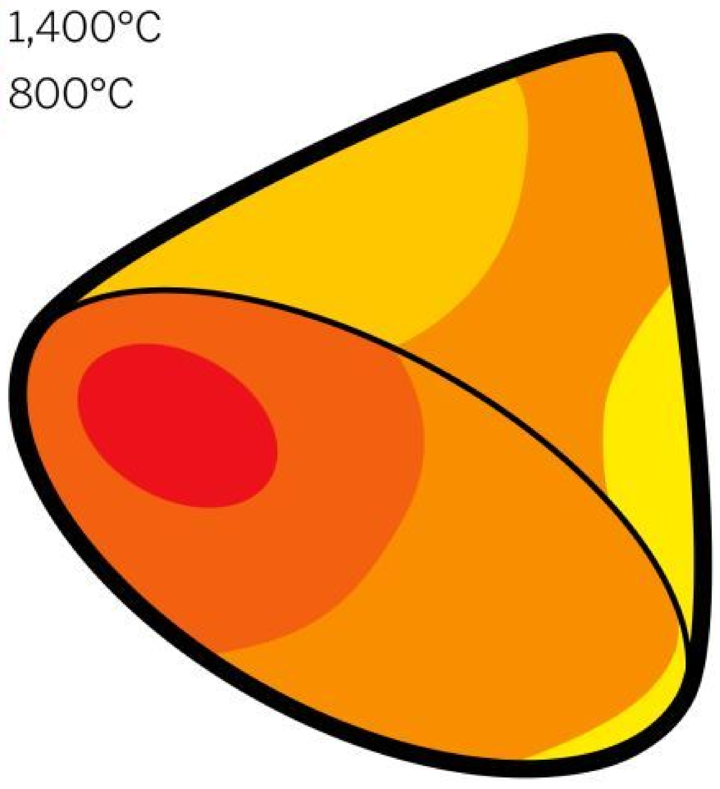
Aft heat shield
This has to withstand the highest temperatures during re-entry, as it faces the direction of motion.

Reaction control engines
These are small rocket motors that control the orientation of the CM during re-entry.

Crew compartment heat shield
The temperatures are less intense here, so the heat shield can be thinner.

Surface temperatures

- 2,760°C
- 2,200°C
- 1,650°C
- 1,400°C
- 800°C

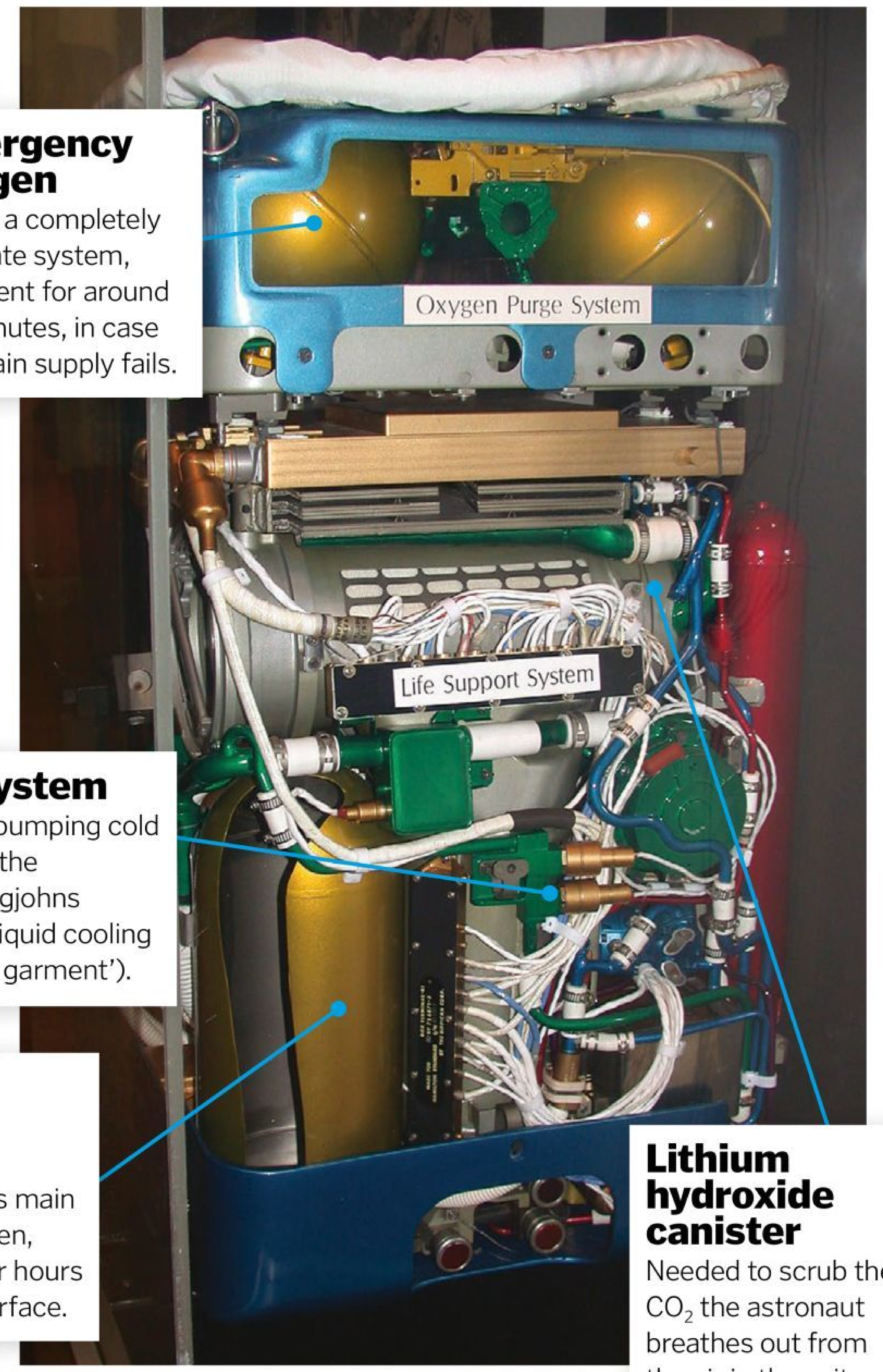


Staying alive with multiple life-support systems

There's no air in space or on the Moon, so the astronauts needed safe and reliable life-support systems. There was one in the CM and one in the LM, as well as a portable life-support system (PLSS) in the backpacks Armstrong and Aldrin wore for their Moonwalk. The Earth's atmosphere is around 80 per cent nitrogen, but humans don't need that to breathe, so instead the astronauts used pure oxygen at a third of normal pressure.

That was the easy part. They also needed to get rid of the carbon dioxide (CO_2) they exhaled, which can be very dangerous if it builds up. Fortunately there's a powdery chemical called lithium hydroxide (LiOH) that absorbs CO_2, and the Apollo missions used LiOH canisters to 'scrub' CO_2 from the air.

A rear view of Aldrin on the Moon, showing the bulky PLSS backpack



Emergency oxygen
This is a completely separate system, sufficient for around 30 minutes, in case the main supply fails.

Cooling system
This works by pumping cold water through the astronaut's longjohns (technically a 'liquid cooling and ventilation garment').

Primary oxygen supply
The astronaut's main source of oxygen, enough for four hours on the lunar surface.

Lithium hydroxide canister
Needed to scrub the CO_2 the astronaut breathes out from the air in the suit.

> "Viewers around the world remained glued to their sets"

The effects of too much CO_2

0.04% Earth-normal concentration → **1%** Drowsiness → **3%** Strain on heart; hearing difficulties → **8%** Loss of consciousness and eventually death

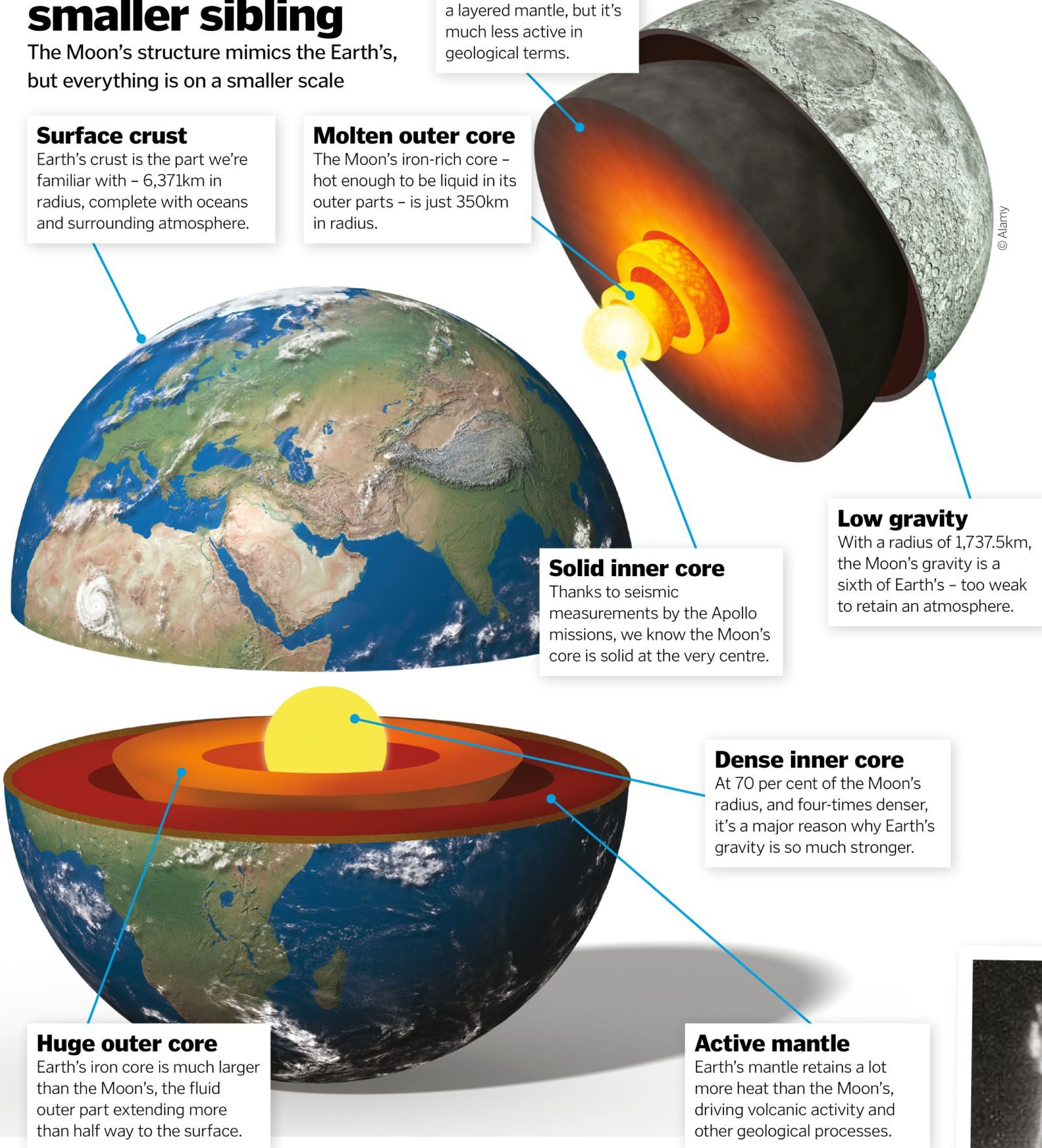
Surviving re-entry into Earth's atmosphere

When the returning Command Module hit the Earth's upper atmosphere, it did so at enormous speed – comparable to the speed it left at, around 11 kilometres per second. Although the atmosphere is extremely thin at high altitude, it's compressed by the impact of the spacecraft, and this compression produced a fierce heating effect. The surface of the CM got close to 3,000°C, and it would have burnt up like a meteor if it was unprotected. The outer shell – called an ablative heat shield – did burn off, because that's what it was designed to do. The heat shield not only protected the astronauts inside, but by absorbing the energy of re-entry it slowed the craft to the point it could use its parachutes.

It looks like a meteor, but it's the Apollo 8 Command Module re-entering the atmosphere

Inside Earth's smaller sibling

The Moon's structure mimics the Earth's, but everything is on a smaller scale



Walking on the lunar surface

20 July 1969 20:17:39 UTC
The LM, with Neil Armstrong and Buzz Aldrin on board, touches down in the Sea of Tranquillity.

21 July 1969 02:56:15
Armstrong steps onto the lunar surface – "One small step for a man, one giant leap for mankind."

21 July 1969 03:15:16
Aldrin joins Armstrong on the lunar surface – initial glitches have been fixed and TV quality is better now.

21 July 1969 03:41:43
The astronauts erect a specially designed flag, which appears to wave in a nonexistent wind.

21 July 1969 03:48:30
Armstrong and Aldrin break off from more important tasks to take a phone call from US President Richard Nixon.

21 July 1969 04:27:42
Time for some science – deployment of passive seismometer, part of the Early Apollo Scientific Experiments Package.

21 July 1969 05:11:13
Armstrong and Aldrin go back into the LM, having spent just over two hours walking on the Moon.

21 July 1969 17:54:00
The LM's ascent stage blasts off on its return trip to the CM in lunar orbit.

Broadcasting live from the Moon

When Neil Armstrong took his first step onto the Moon, he was watched by a worldwide TV audience estimated at around 650 million – the biggest in history up to that point. Yet getting those TV pictures back to Earth in a matter of seconds was pushing the limits of 1960s technology. The main bottleneck was the Lunar Module's tiny antenna, which was limited to a bandwidth of just 500kHz – less than a tenth of a normal TV signal. The result was a grainy, flickering, black-and-white picture made up of 200 scan lines running at just ten frames per second.

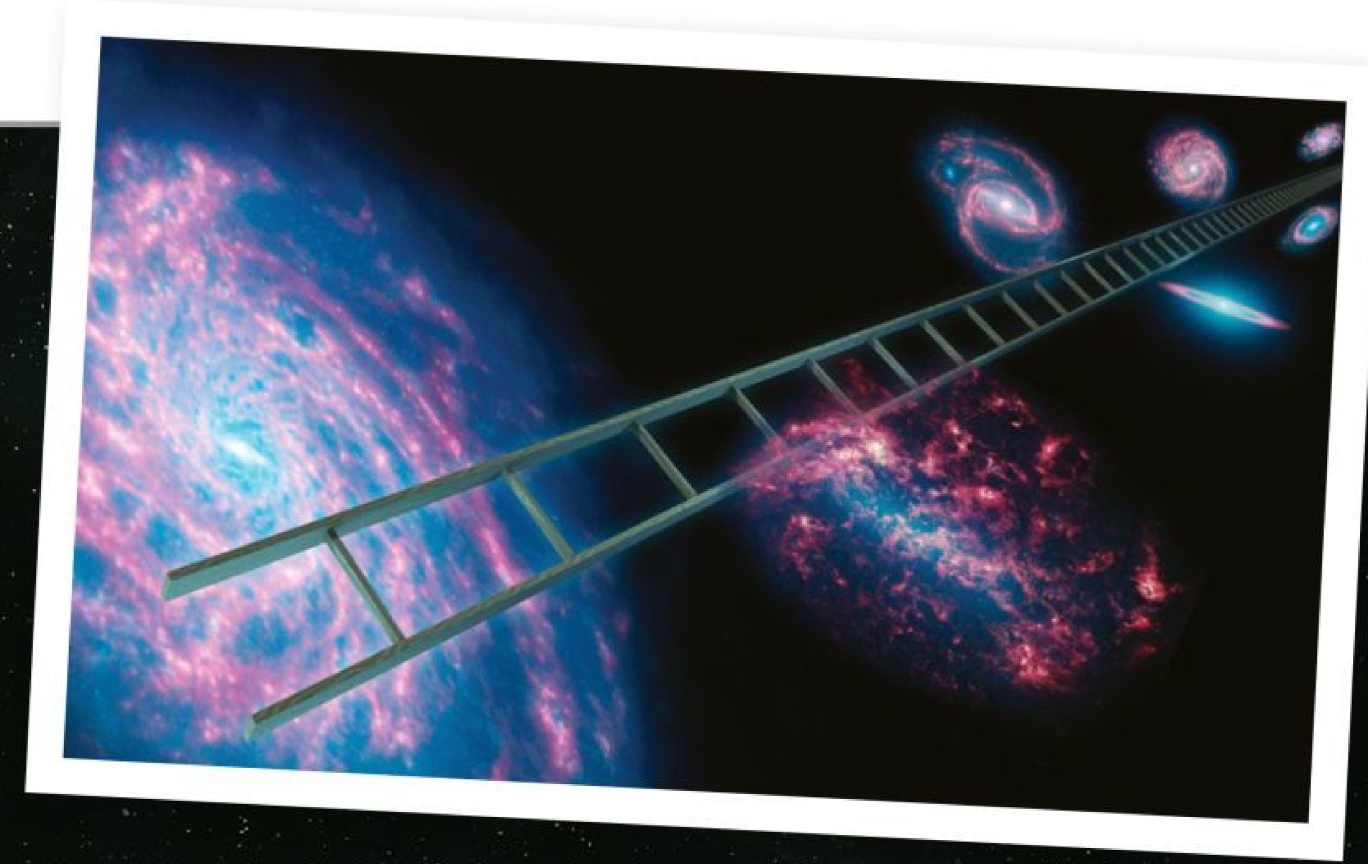
To make matters worse, the first images from the surface, as Armstrong began to descend the ladder, were upside down. That was quickly put right, but then an anomaly at the ground station in California produced a thick black bar across the screen, marring the audience's view of Armstrong's 'giant leap for mankind'. But it was one of history's greatest moments, and viewers around the world remained glued to their sets for the entire two hours the astronauts were walking on the Moon.

The UK, of course, was no exception, and both the BBC and ITV covered every moment of the lunar mission throughout the night. That might not sound very exceptional today, but this happened in the days before there was 24-hour television, and the Apollo 11 coverage was Britain's first ever all-night broadcast.

The live TV images from the Moon were historic but poor in quality

Determining the size of the universe

Measuring the enormity of space is a task best left to the professionals – and even they don't know!



Standard candles are just one of the methods used in the Cosmic Distance Ladder

The universe is a vast space that is simply incomprehensible to the human mind. The distance between London and New York is considered a large distance by many, but it pales in comparison when you think that it would take 2.5 million years to get to our closest galaxy while travelling at the speed of light.

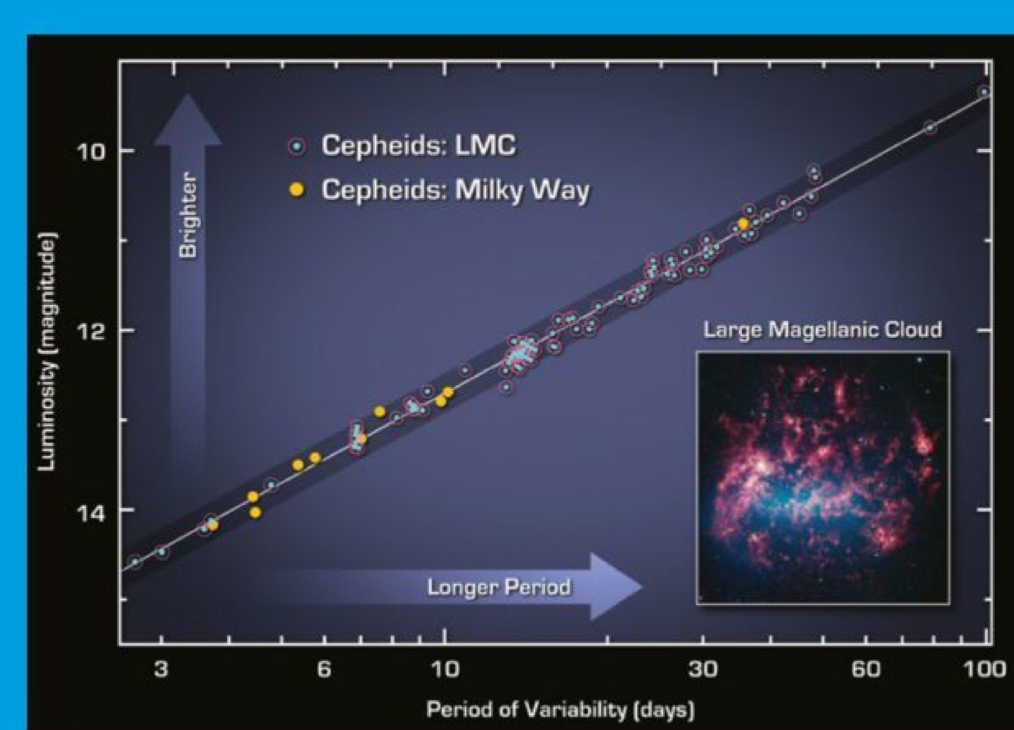
Astronomers have spent decades trying to determine the size and age of the universe, and their closest estimate to the size of the observable universe is 46 billion light years across. This is just the area that astronomers can observe, and in fact they think it could even be double that size. The way they have managed to estimate such a number is through the use of astronomical distance measuring beacons that are known as 'standard candles'.

The premise is simple. In the same way that you know what the brightness of a candle is while you hold it in front of you, it will gradually appear dimmer the farther it is from you. By measuring the difference in actual and perceived brightness, the distance between you and the candle can be determined. Astronomers use the same method on astronomical objects, and in the case of this research, a group of stars known as Cepheid variables are used. They have been studied for a long time using telescopes such as NASA and ESA's Hubble Space Telescope, and provided help in deducing this mind-boggling figure.

How brightness variability can measure distance

Cepheid variables are stars that are extremely useful when it comes to measuring cosmological distances. They are unlike the Sun in that they are usually between four and 20 times more massive than our own star and are much further along in their lifetime. At this later stage, they exhibit a brightness variation due to an inherent instability in the star that causes pulsations and this is used to calculate distances of a few tens of millions of light years.

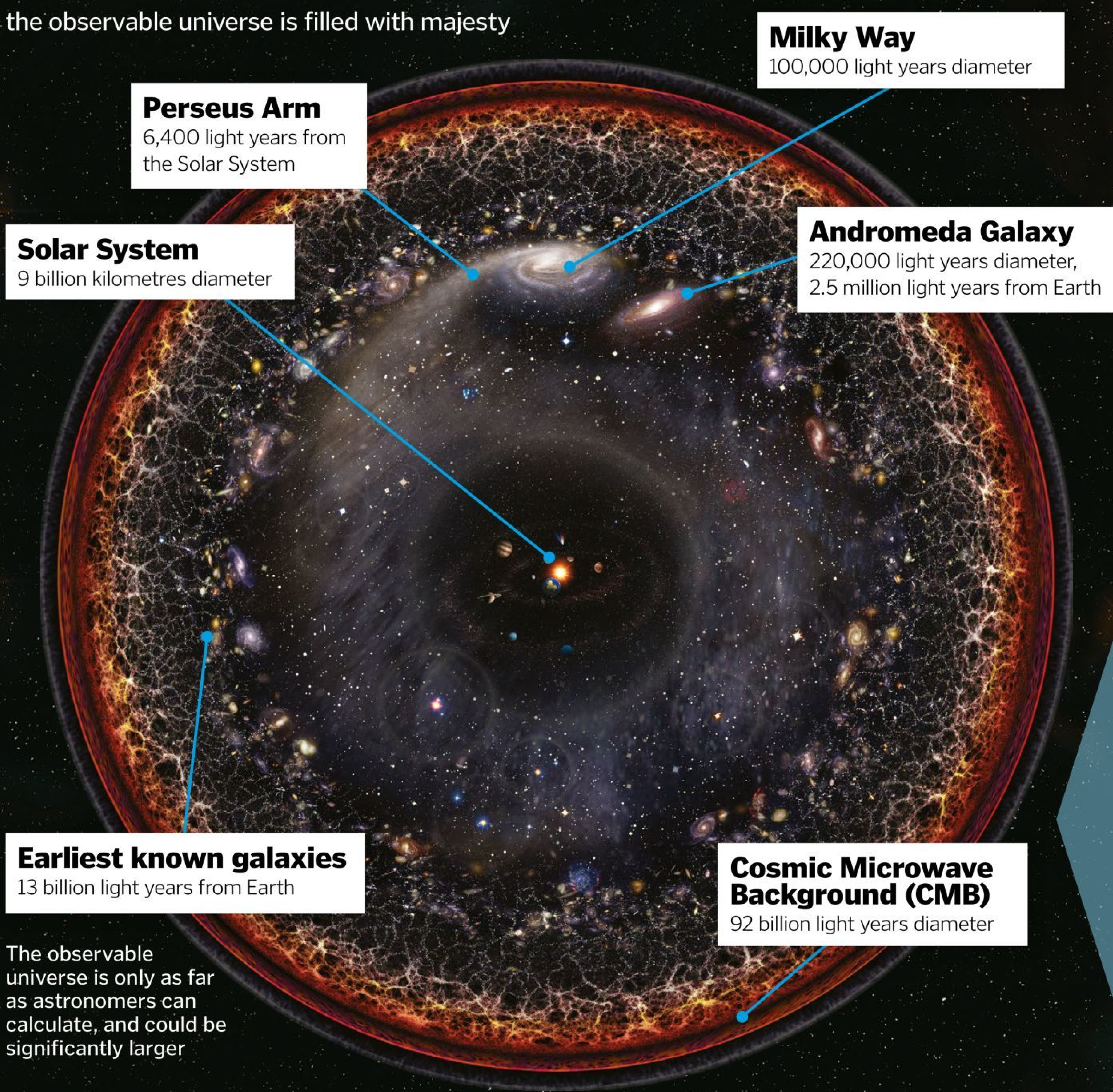
Astronomers determine the rate of this pulsation, which is the period of variability, of the Cepheid, which has its brightness (or luminosity) inferred by the 'period-luminosity relationship'. The longer their variation the brighter the star is and vice versa. From this relationship, astronomers can use Cepheids as standard candles in their mission to measure the universe.



The timing of a Cepheid pulse is related to its luminosity allowing a distance to be calculated

Putting the universe into scale

From the Solar System to the Cosmic Microwave Background, the observable universe is filled with majesty



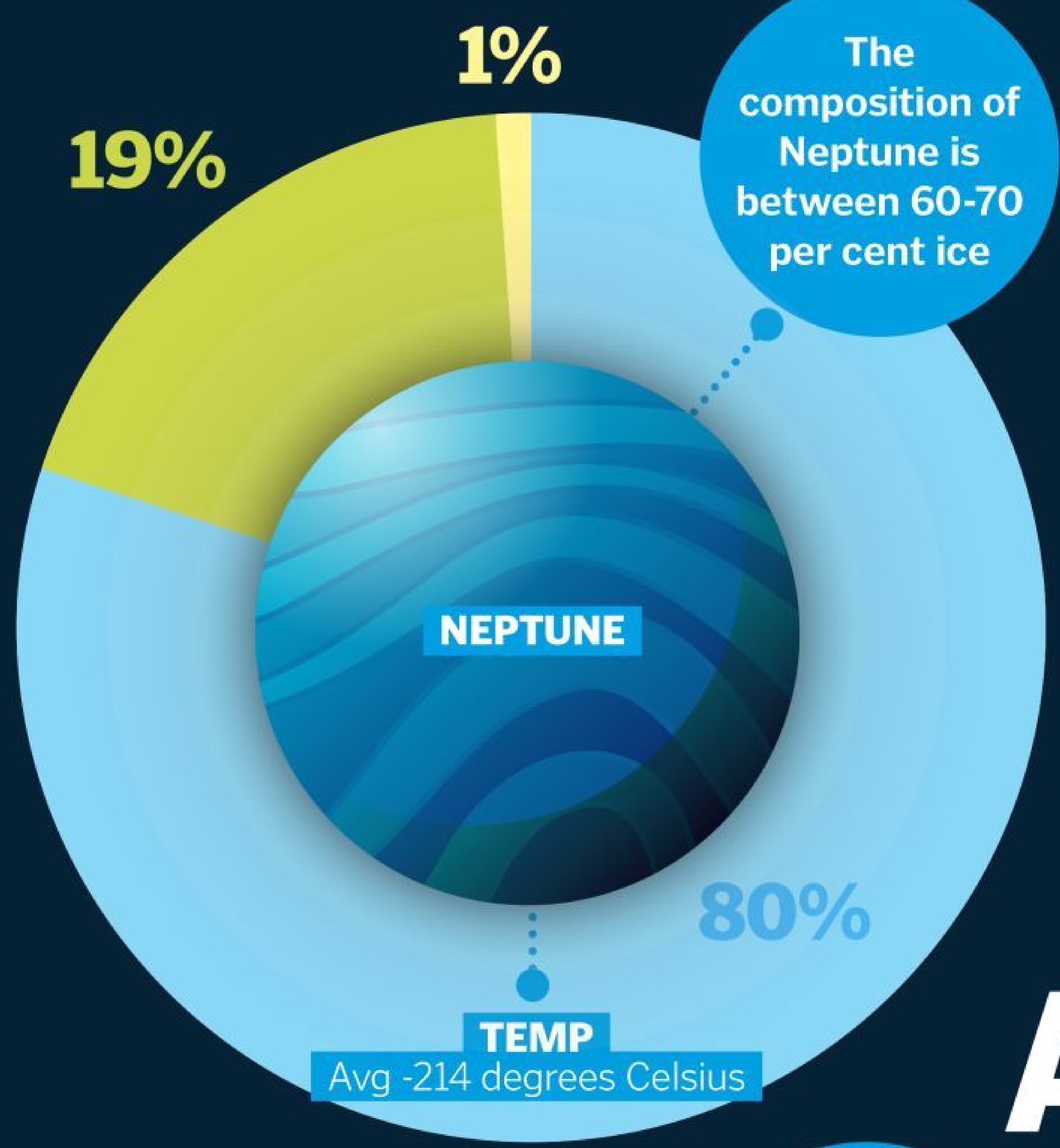
The observable universe is only as far as astronomers can calculate, and could be significantly larger

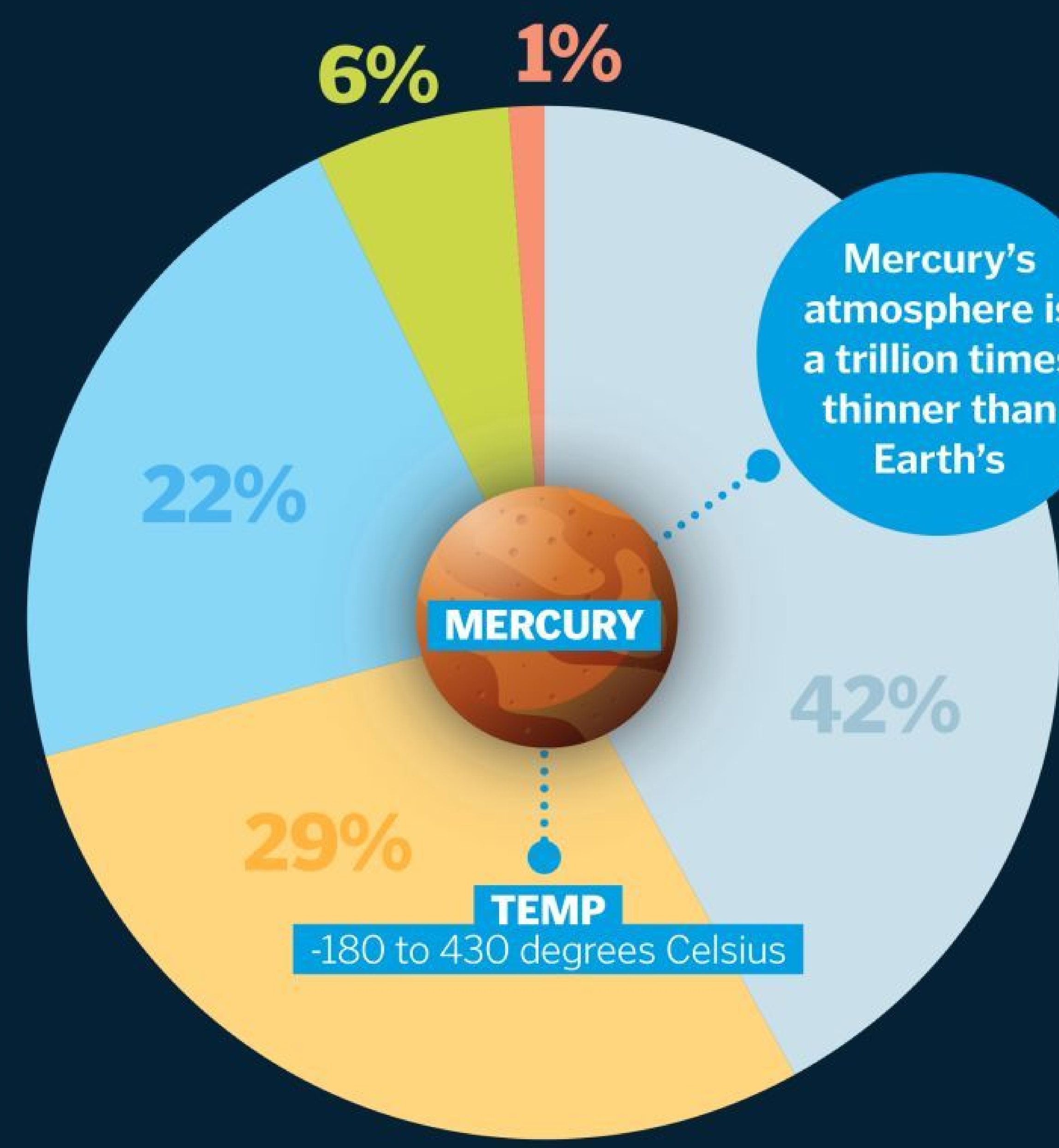
The universe beyond our Solar System

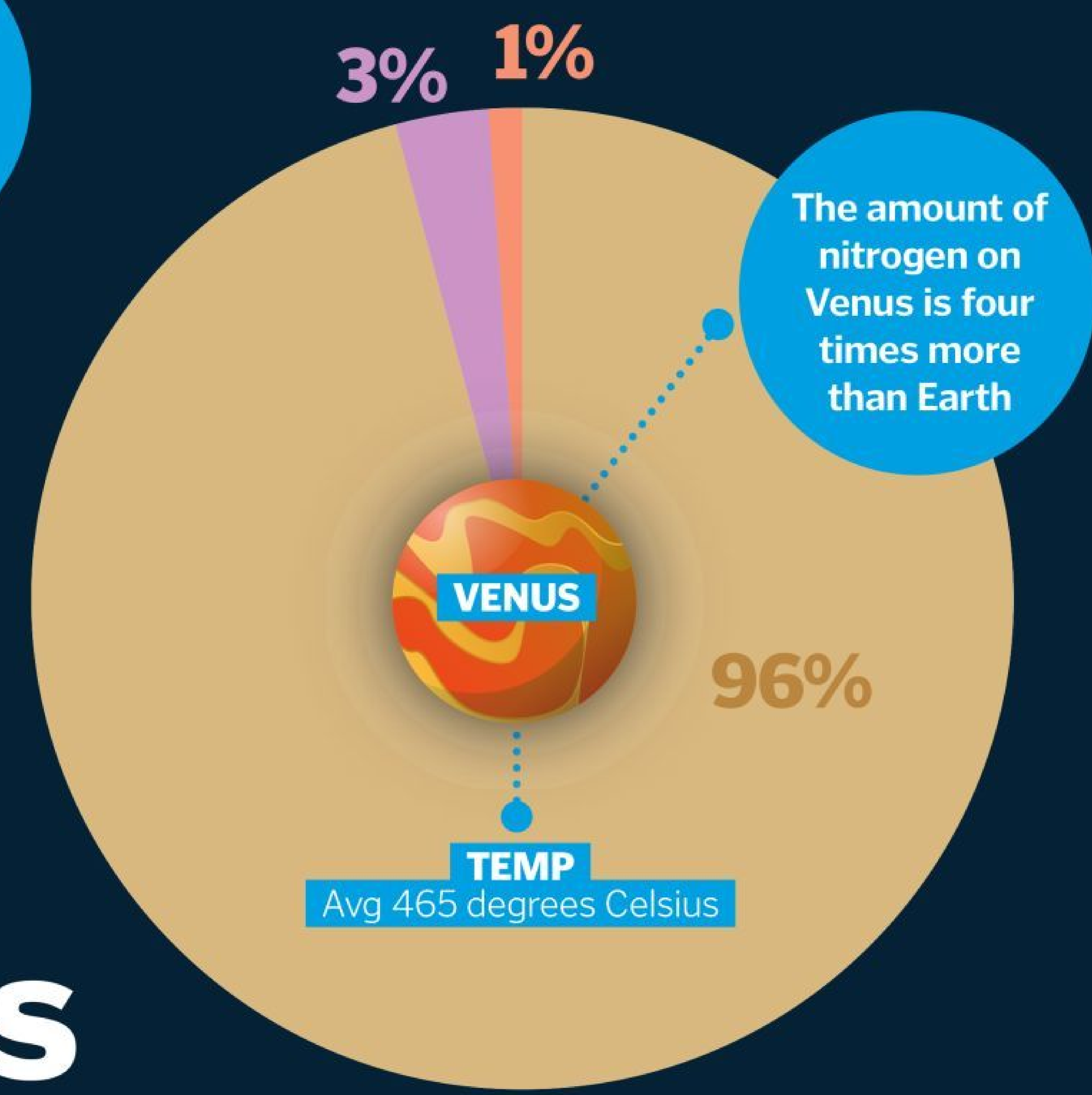
Nicolaus Copernicus may have something to say about this picture, but it's not saying the Solar System is at the centre of the universe. It's an illustrated logarithmic scale concept of the universe we can see. This piece was created by Pablo Carlos Budassi, a musician and artist, and inspired by logarithmic maps created by researchers at Princeton University, New Jersey, US. The picture was created to show how the universe changes logarithmically the further we peer beyond our Solar System, showing stars, galaxies and even the gas created after the Big Bang.

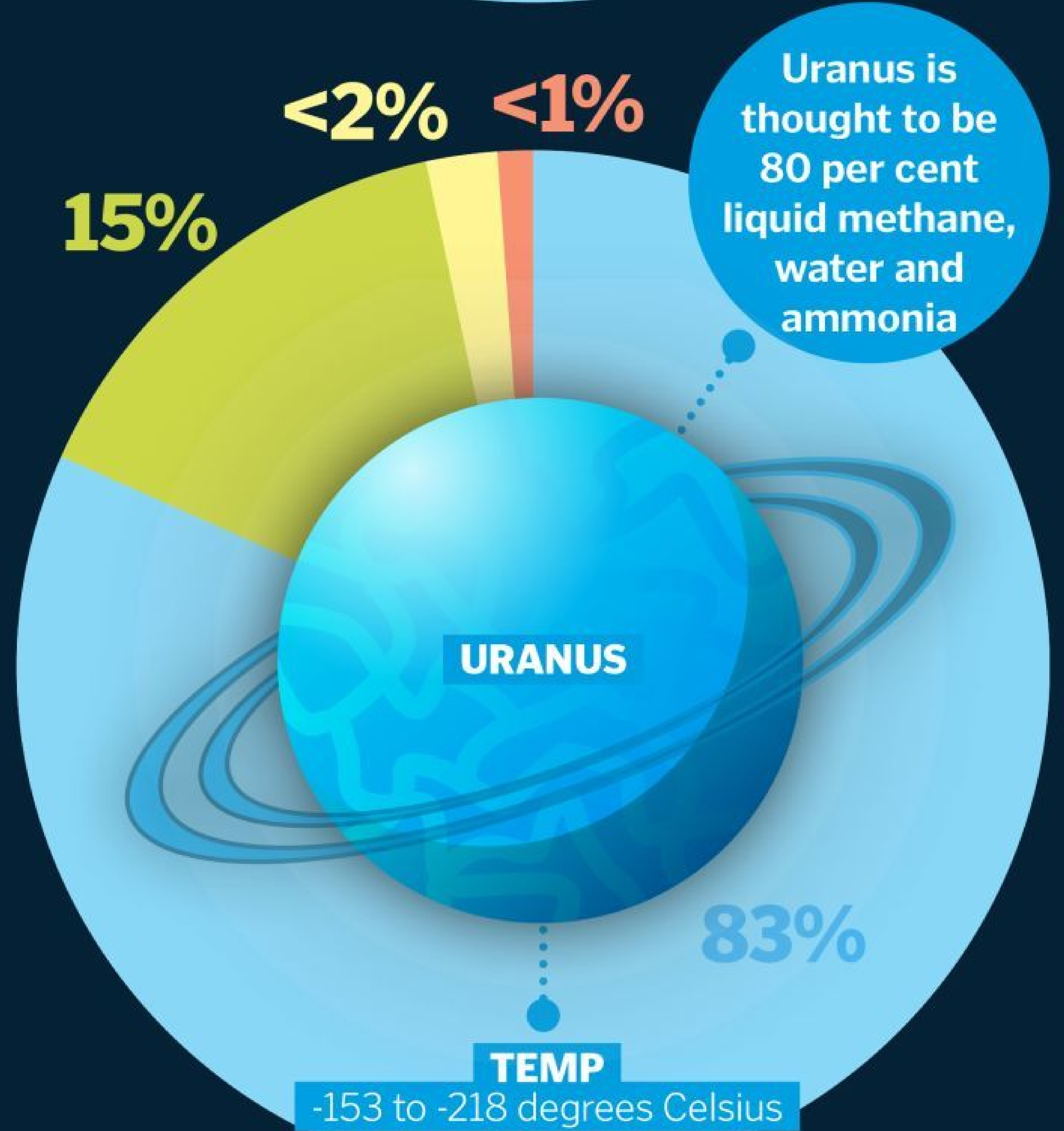
Atmospheres of the eight planets

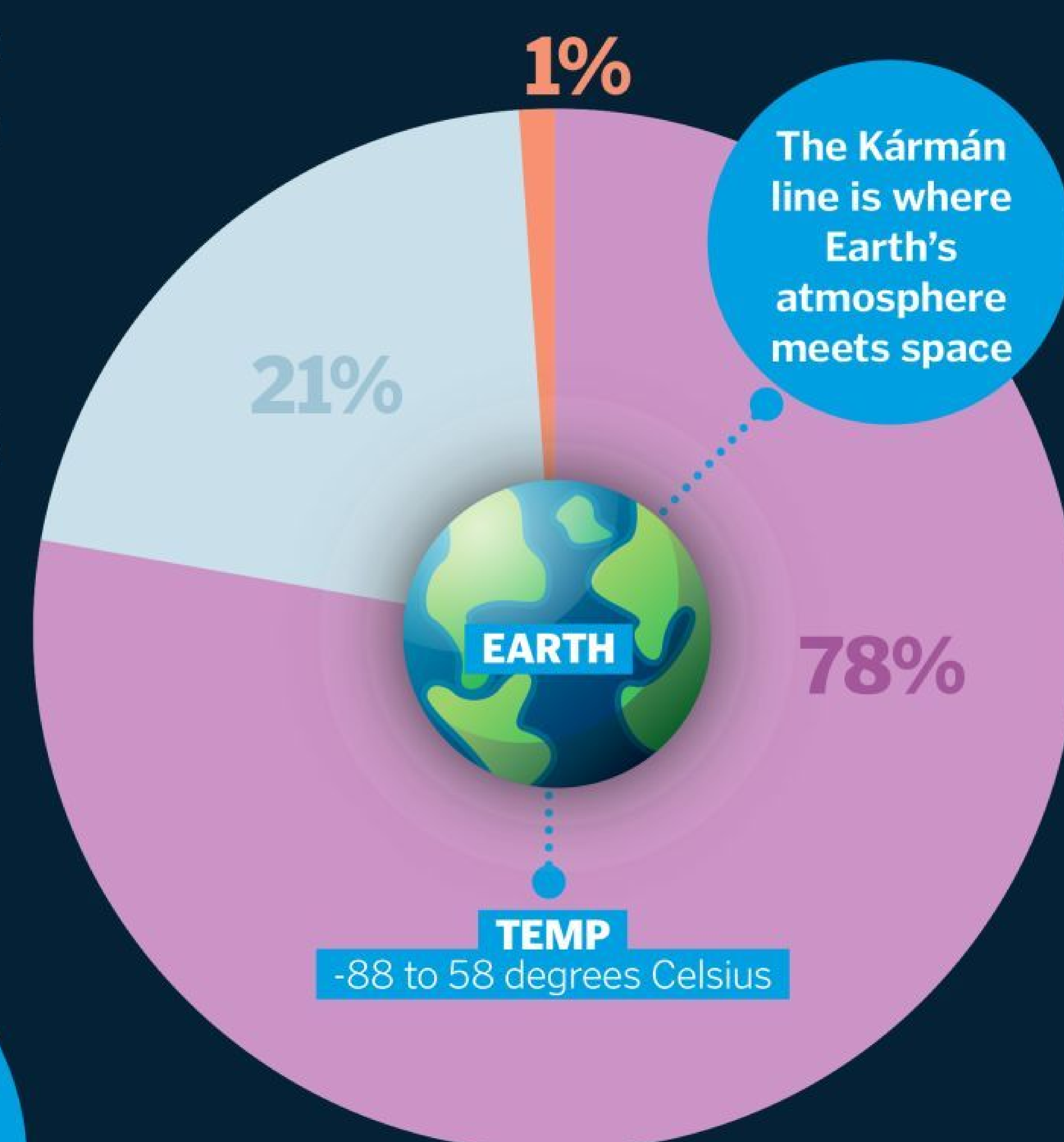
With volatile gases and crushing pressures, some places in the Solar System aren't quite as pleasant as Earth...





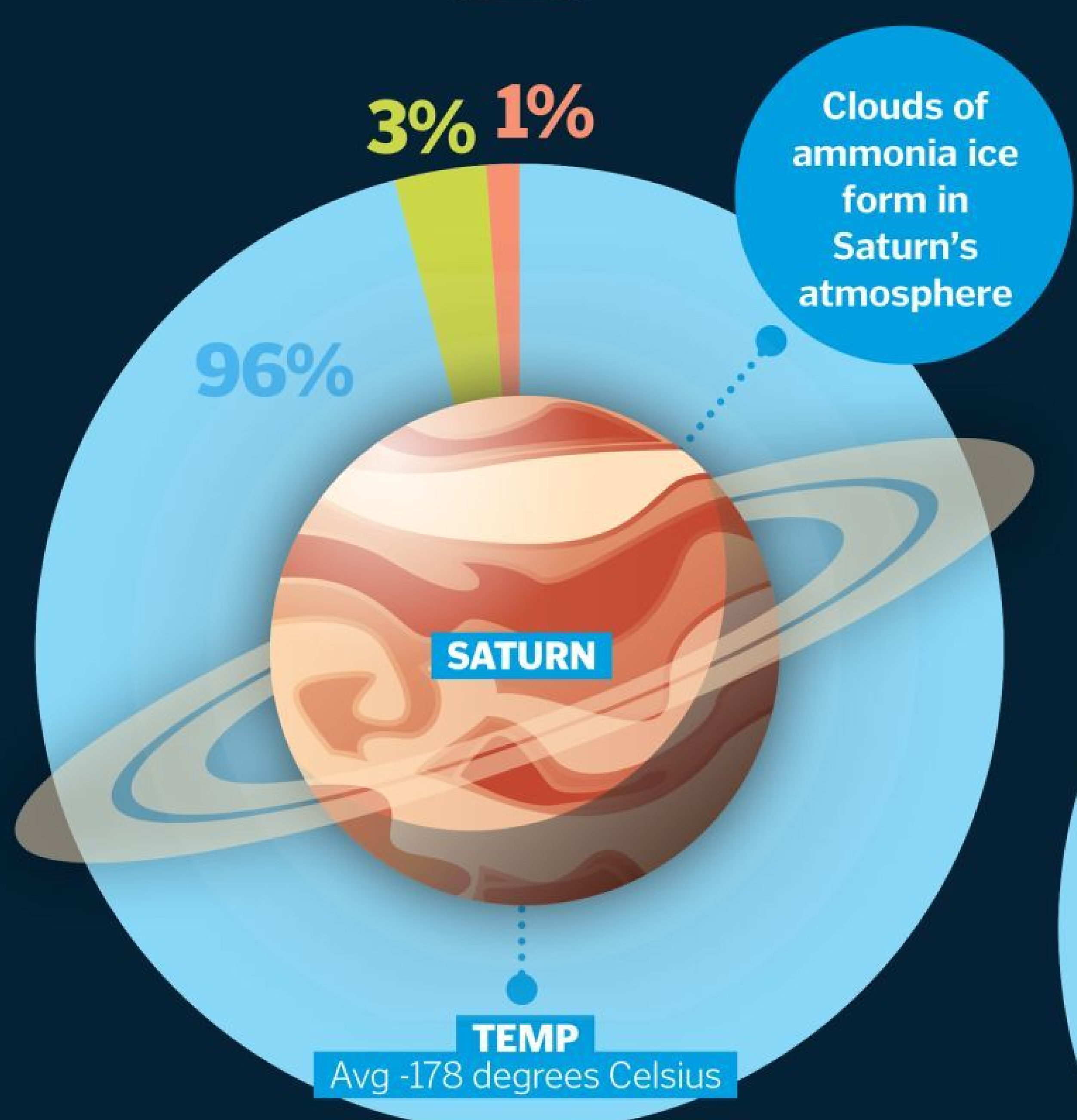


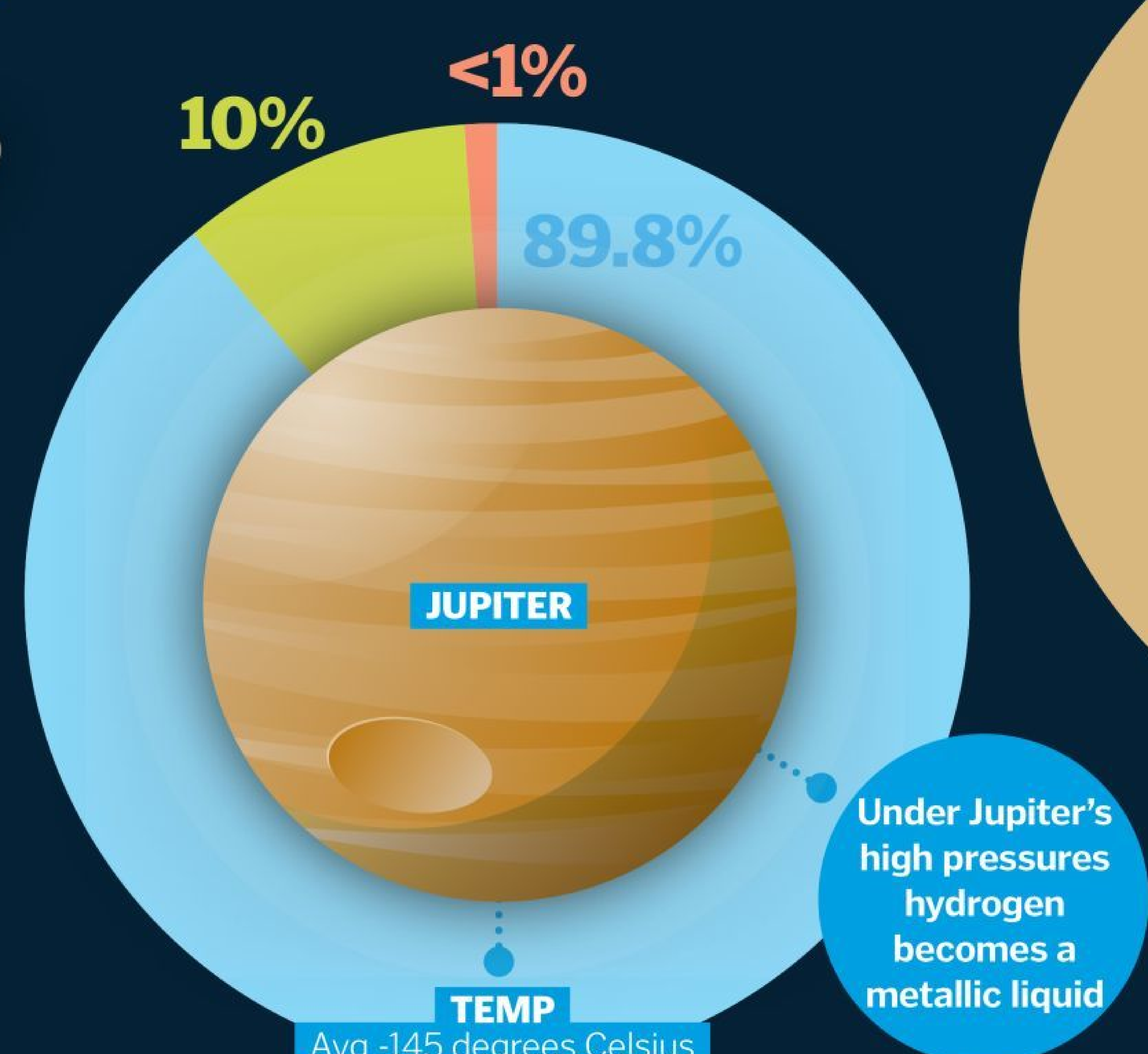


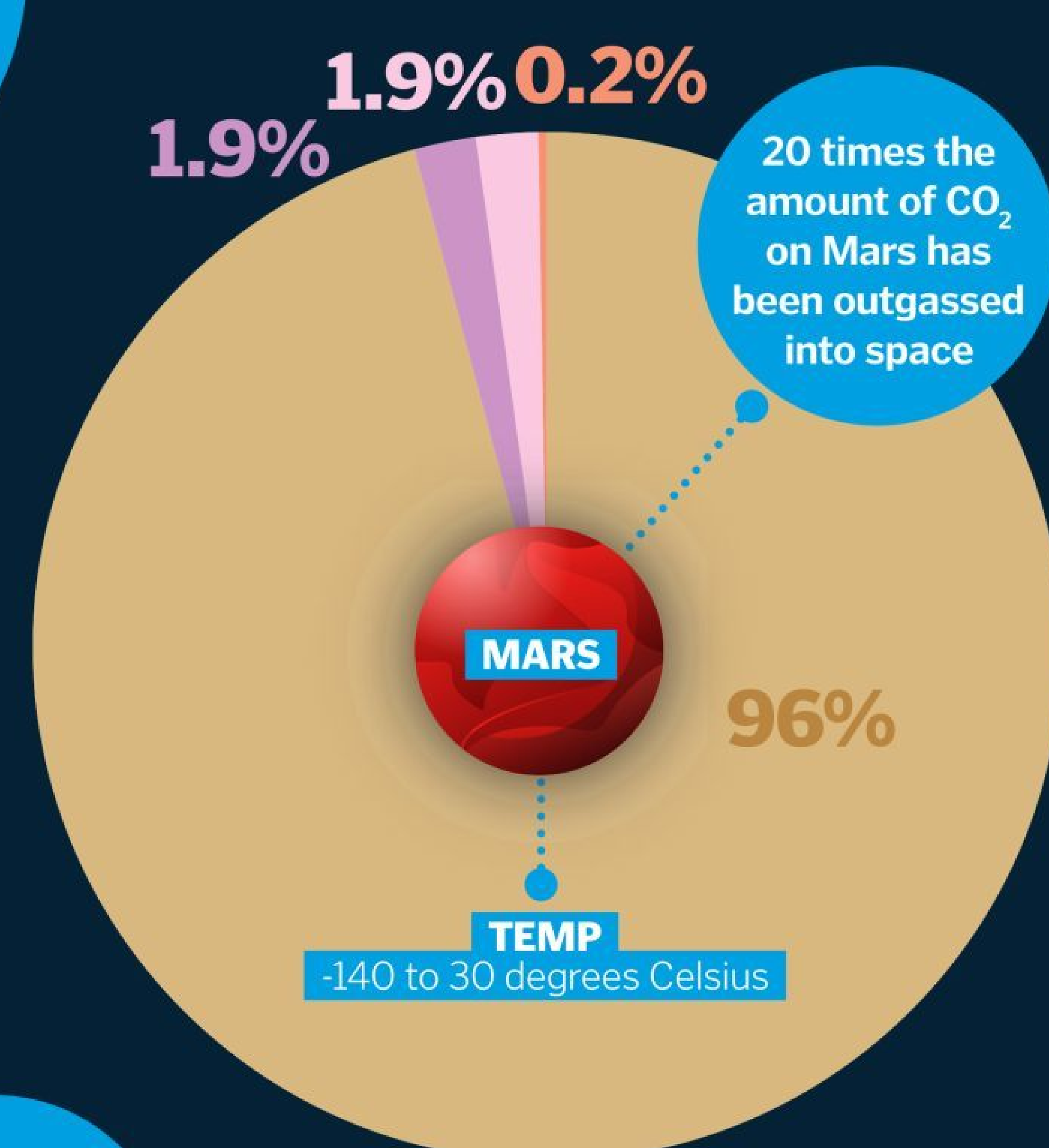


- Nitrogen (N_2)
- Carbon dioxide (CO_2)
- Oxygen (O_2)
- Sodium (Na)
- Hydrogen (H_2)
- Helium (He)
- Methane (CH_4)
- Argon (Ar)
- Other

Due to their distance from the Sun, the atmospheres of dwarf planets such as Eris and Makemake collapse, forming snow and ice on the surfaces, before thawing when nearer the Sun







INSIDE T

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THE RED LANET

NASA's InSight lander will tell us more about the interior of Mars than ever before

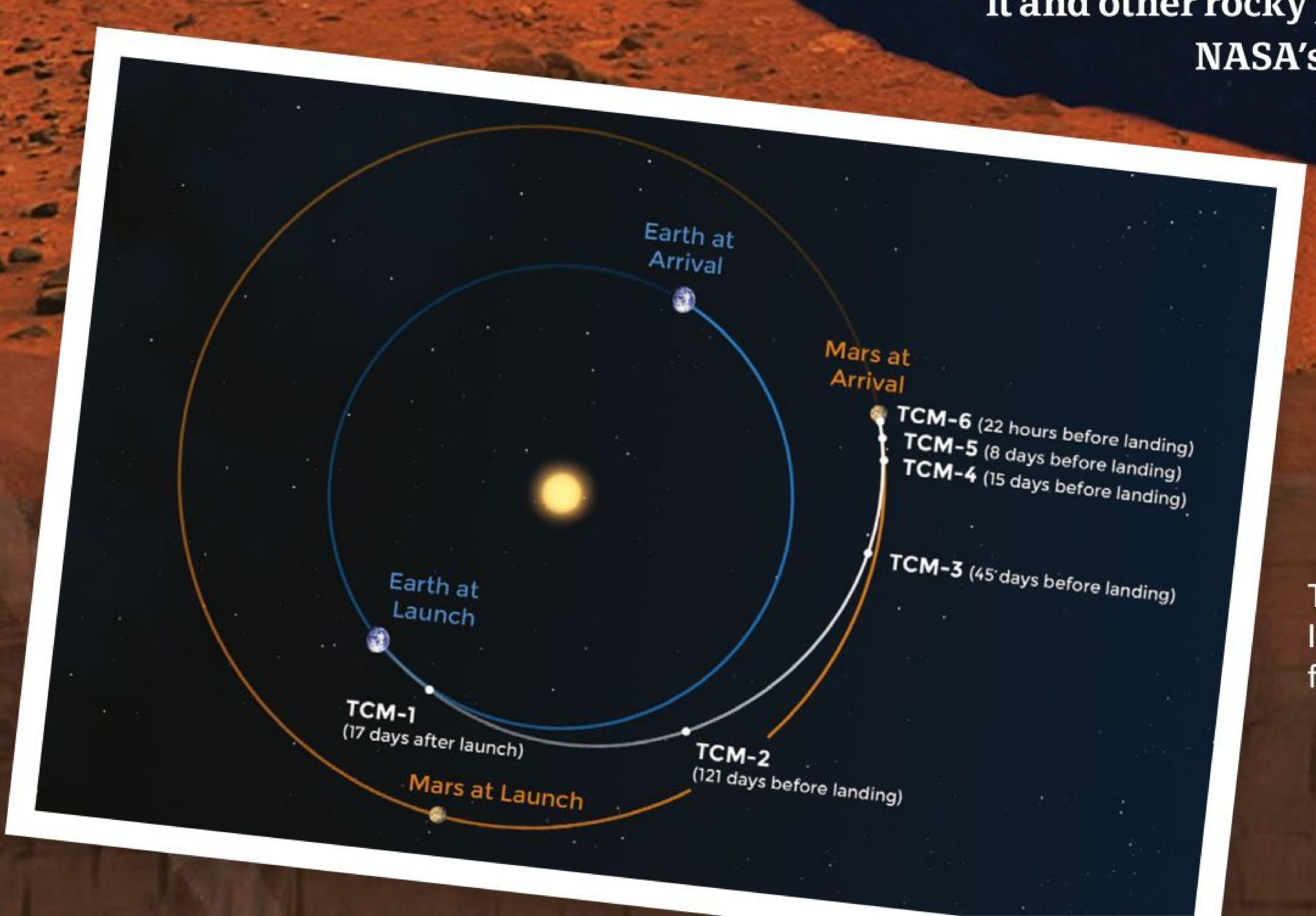
Words by **Jonathan O'Callaghan**

Over the last five decades we have sent a host of missions to Mars. Some have been orbiters, designed to image the planet from afar. Others were rovers sent to probe the surface and analyse rocks at different locations. But now a new mission will do something we've never done before – it will try and peer inside Mars itself, telling us not only what the planet is made of, but how it and other rocky planets formed.

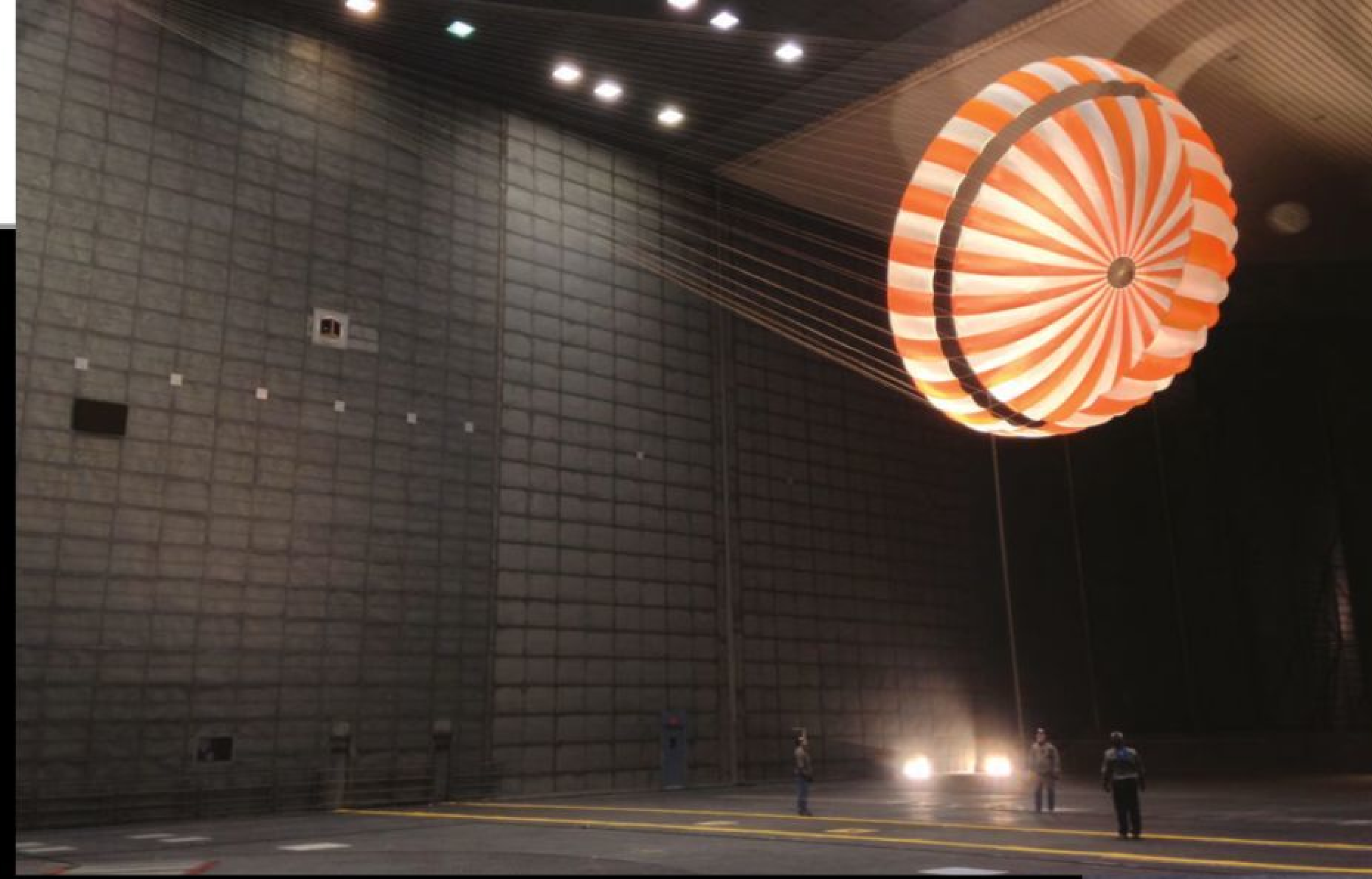
> "InSight will try and peer inside Mars itself"

NASA's InSight mission was launched on 5 May 2018 from the Vandenberg Air Force Base in California on an Atlas V rocket. After a journey of about 485 million kilometres, it touched down on Mars on 26 November 2018. Mars is hard, and many missions have failed, so there was always a chance InSight wouldn't make it. Thankfully it did, and these next few pages will run through what this pioneering mission will do on Mars for just over one Mars year (two Earth years).

InSight is a stationary lander, like NASA's Phoenix lander on Mars in 2008, which means it won't be roving around the surface. Instead, it will touch down in a location near the equator called Elysium Planitia, where it will stay for the entirety of its mission. This region was picked for a number of reasons, one being that it is relatively smooth, thereby minimising any problems when landing and providing an easy environment in which to conduct science. It also has an abundance of sunlight, meaning InSight's solar panels will



This map depicts InSight's trajectory from Earth to Mars



A large parachute helped InSight land on the Martian surface

receive plenty of juice. The landing site is also important for the actual landing itself, giving the spacecraft enough atmosphere to slow itself down.

To touch down on Mars, other spacecraft have relied on airbags or a sky crane system with thrusters, as in the case of the Curiosity rover in 2012, to land on the surface. InSight is a little bit different. First, about seven minutes before it entered the atmosphere it jettisoned the cruise engine that took it to Mars. It then entered the atmosphere at about 21,240 kilometres per hour, with a heat shield taking the brunt of the entry. Temperatures reached approximatelt 1,500 degrees Celsius as InSight descended.

Roughly three and half minutes after entering the atmosphere InSight deployed its parachute 12 kilometres above the surface, travelling at 1,500 kilometres per hour. The spacecraft descended with its parachute for about three minutes, using its radar to sense the distance to the ground and extending its three legs. Then, 1.2 kilometres above the surface, it used 12 descent engines to slow itself down, bringing it to a relatively gentle touchdown at 8.7 kilometres per hour.

> "Once on the surface, the real fun begins"

Once on the surface, the real fun began. The lander got to work immediately, unfurling its ten-sided solar panels to create a collection area the size of a ping-pong table. On top of the lander are its various instruments and pieces of equipment, a smorgasbord that a robotic arm with a mechanical hand will be able to grab and place on the surface. Before it did this, though, it used two onboard cameras to image the surrounding area and pick the best place to deploy its instruments.

These instruments are designed to study Mars in a whole new way. Previous missions have focused on the surface, but InSight will be looking underground. Of particular interest is trying to work out what is actually inside Mars and how similar its interior is to Earth. While both planets are rocky, Mars is now a relatively dead and dusty world. Under its surface could be a whole different matter, however, so a seismometer experiment called the Seismic Experiment for Interior Structure (SEIS) will be placed on the surface to try and listen to seismic waves travelling throughout Mars. These are produced by so-called 'marsquakes' in a number of ways, one being meteorites hitting the surface, another being the planet cooling and contracting, and another being magma rising up from its suspected moulten core.

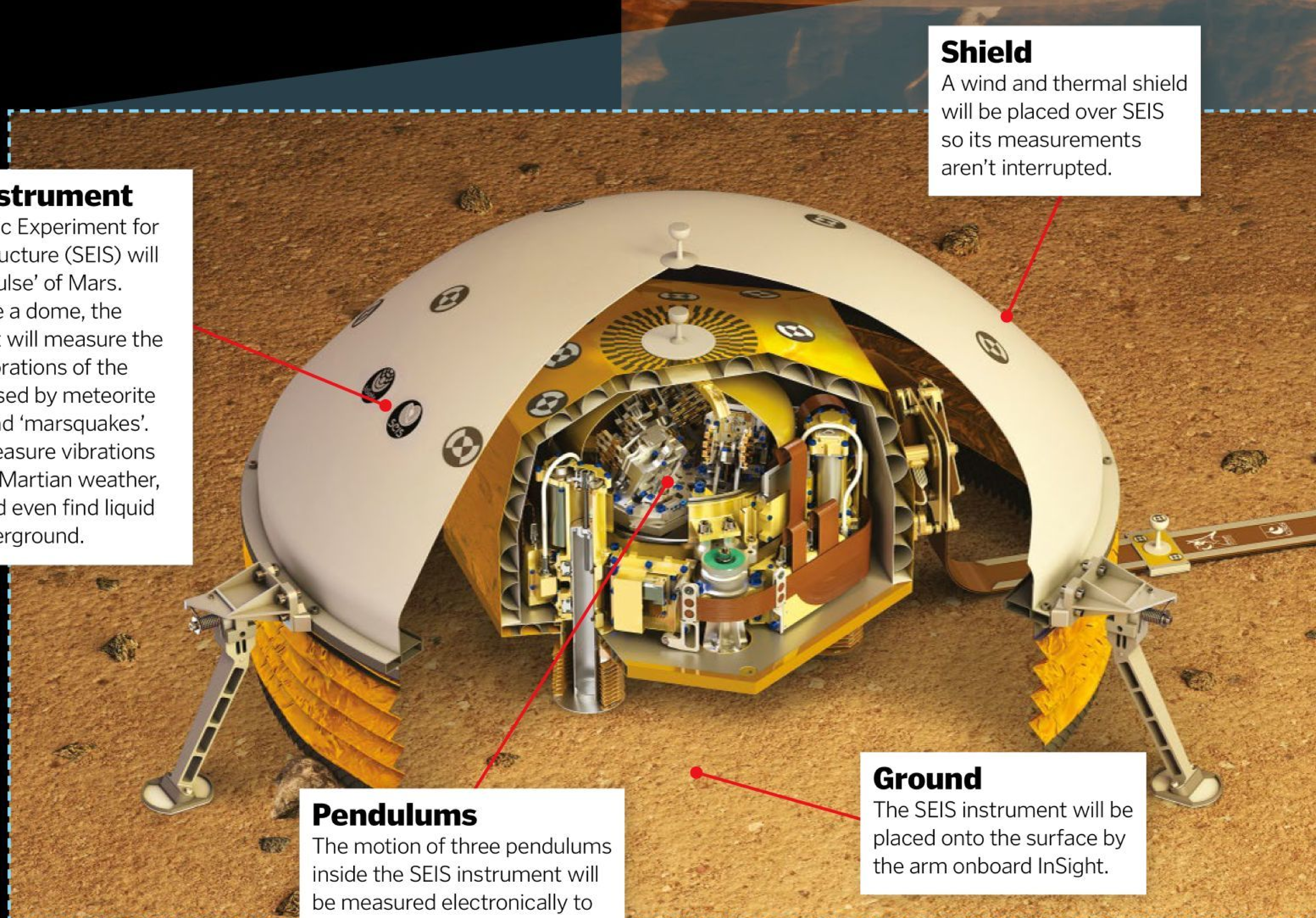
By monitoring these waves and measuring their speed, frequency and size, the seismometer will be able to work out what material is inside Mars. We don't actually know if the core of Mars is solid or liquid, something this experiment could reveal. We also don't know how thick its next two layers are, the mantle and crust, the former likely rich in silicon and the latter made of less-dense rocky material. Studying exactly what Mars is made of, and how its structured, could not only tell us about the Red Planet itself but others too.

Our Solar System has four rocky planets, but we're starting to find bucket-loads elsewhere in the galaxy. In our Solar System though, only one – Earth – became the habitable, pleasant world it is today. Understanding the formation and structure of Mars could help tell us why Mars is not the

InSight's equipment

How this lander will study the surface of Mars like never before

Solar arrays
Two ten-sided solar arrays, each 2.15m across, will deploy on the surface to provide power to the lander.



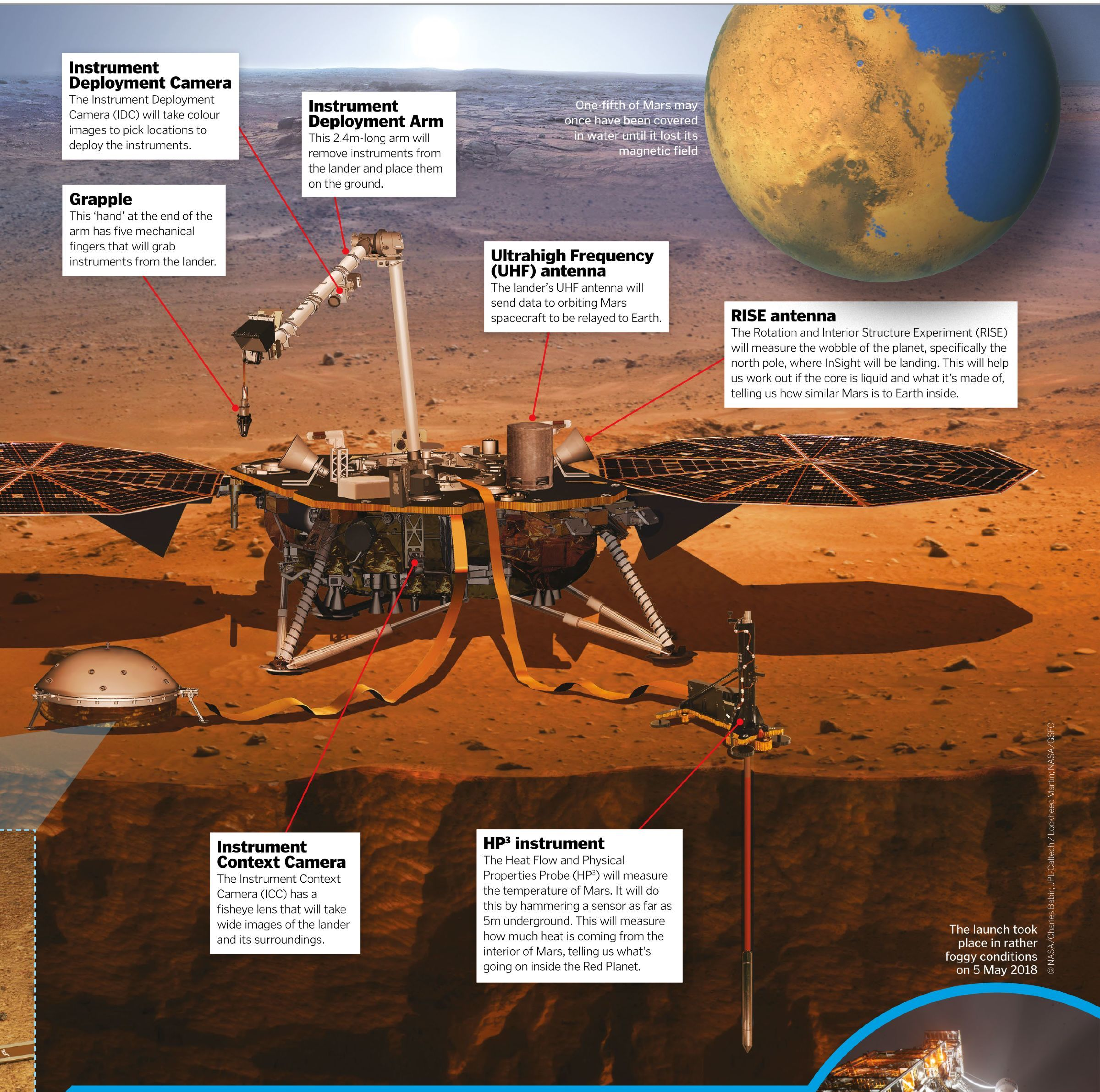
Shield
A wind and thermal shield will be placed over SEIS so its measurements aren't interrupted.

SEIS instrument
The Seismic Experiment for Interior Structure (SEIS) will take the 'pulse' of Mars. Shaped like a dome, the instrument will measure the seismic vibrations of the planet caused by meteorite impacts and 'marsquakes'. It'll also measure vibrations caused by Martian weather, and it could even find liquid water underground.

Pendulums
The motion of three pendulums inside the SEIS instrument will be measured electronically to detect vibrations.

Ground
The SEIS instrument will be placed onto the surface by the arm onboard InSight.

DID YOU KNOW? *InSight is the first lander to ever use a robotic arm to grasp instruments on the surface of another planet*



The launch

InSight was launched from Vandenberg Air Force Base on the central coast of California on 5 May 2018. That choice of launch site was somewhat unusual, as missions to other planets usually lift off from NASA's Kennedy Space Center in Florida. From the latter, rockets can launch east over the sea, getting an additional boost to their momentum from Earth's rotation. However, InSight was launched on the powerful Atlas V-401 rocket, which was strong enough that it could launch the spacecraft south from Vandenberg over water.

The launch took place in rather foggy conditions on 5 May 2018

same, although we do think it once had water on its surface just like Earth. Learning how Mars formed differently to Earth will be crucial in understanding the broader picture of what ingredients a rocky planet needs to become habitable.

Helping in this endeavour will be another instrument deployed by InSight called the Heat Flow and Physical Properties Package (HP[3]), developed by the German Aerospace Center (DLR). This is essentially a probe that will be hammered into the surface of Mars up to a depth of five metres, deeper than any instrument on Mars before. A motor will create tension in a spring, which will drive a hammer down a cylindrical shaft into a spike at the bottom called the 'mole', requiring between 5,000 and 20,000 hits over 30 to 40 days depending on how compact the soil is. This will gradually burrow into the ground, and once it reaches its maximum depth, 14 sensors up the tether will begin to measure the temperature at different depths.

Why? Well, the goal of HP[3] is to work out how much heat is flowing out of the interior of Mars and the rate it is doing so as it travels up the sensors. Heat flow is deemed to be a planet's 'vital sign', with heat being crucial to shaping the geology of a planet, from its canyons to its mountains. It can also play a role in delivering water to the surface, and we think there might be some water hiding under the surface of Mars. What's more, if the energy of Mars' core is diminishing – which it might be, as the planet mysteriously lost its magnetic field billions of years ago, one likely powered by an active core – then this instrument could tell us how long Mars has left before it truly dies.

The last main science goal aboard InSight is the Rotation and Interior Structure Experiment (RISE). Unlike the other two experiments, however, this does not have its own dedicated equipment. Instead, it will be using the direct radio connection InSight has with Earth to measure how much Mars is wobbling as it rotates. Amazingly, InSight will use its antennae to measure its location in space to a precision of less than ten centimetres. This will tell us how much the rotation axis of Mars is swaying.

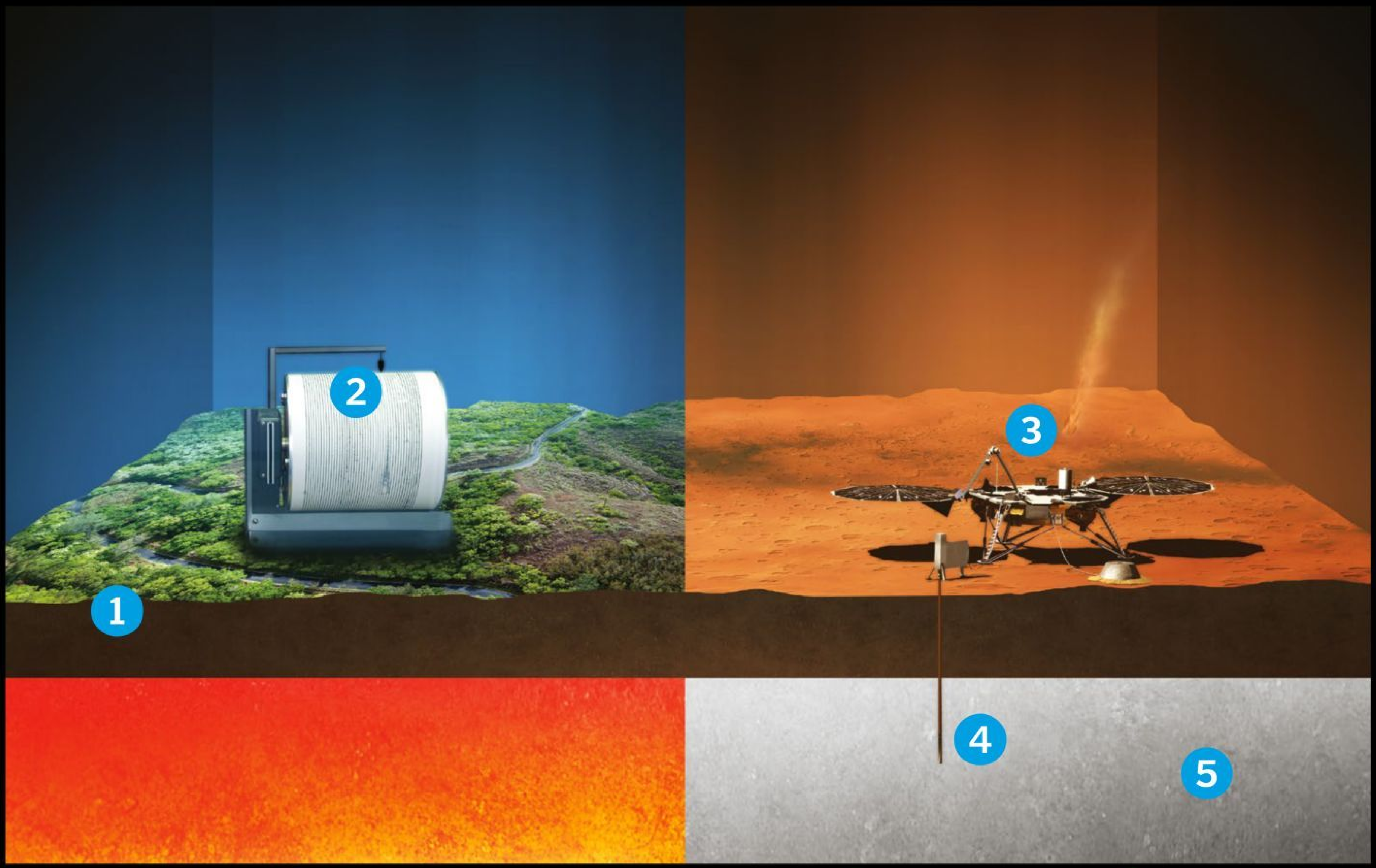
This is important because it will tell us how big the core of Mars is. Previous findings have suggested the core is extremely dense and

> "InSight is a groundbreaking mission"

InSight could tell us more about rocky planets in our Solar System and beyond

Seismic activity

How we can measure seismic activity on Mars compared to Earth



1 Rocks When rocks move or break apart we can measure the seismic waves they produce as they bounce around the planet.

2 Seismometer A seismometer is specifically designed to measure the size, frequency and speed of seismic waves, also called quakes.

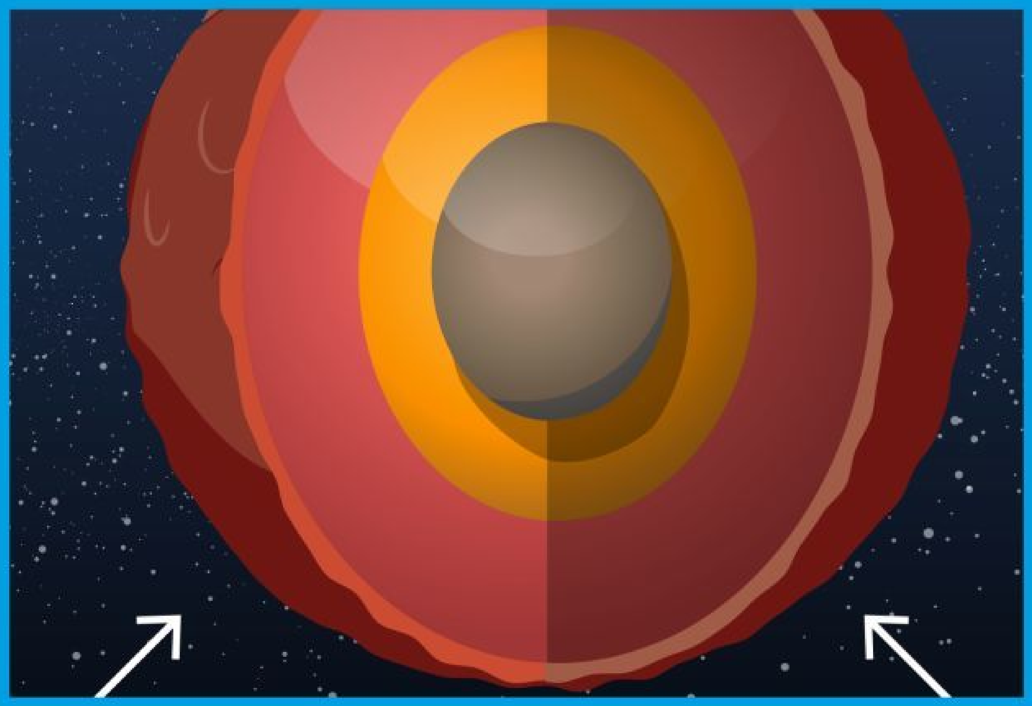
3 Location On Earth we take measurements from multiple locations, but InSight will have to do it from just one.

4 Number InSight is expected to detect up to several hundred seismic waves, as well as quakes produced by meteorite impacts.

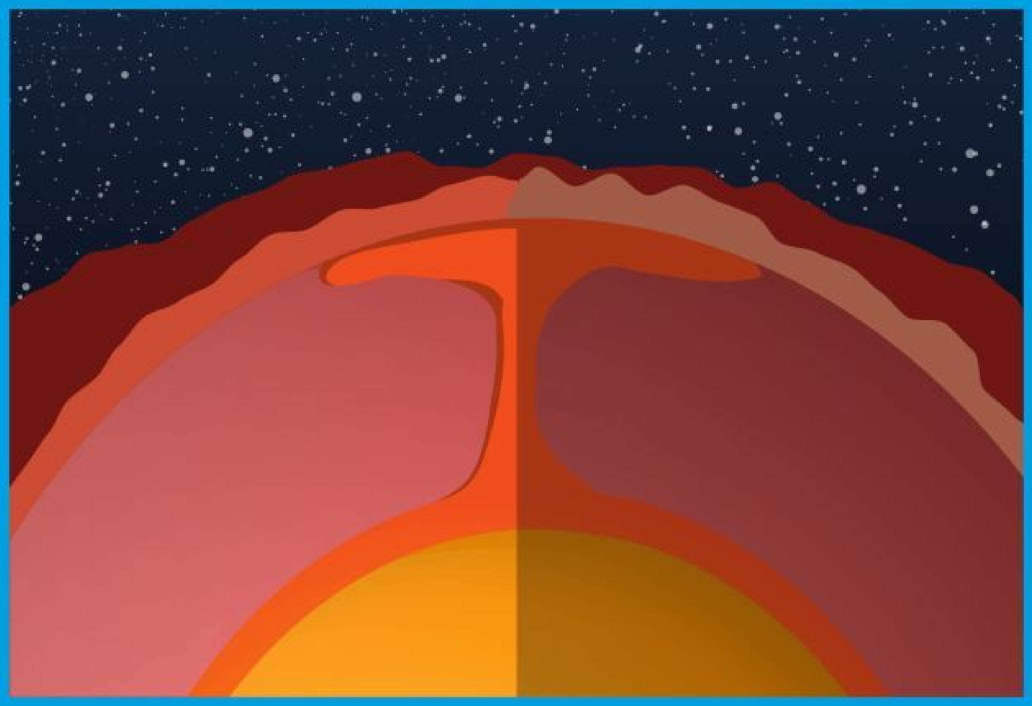
5 Material Detecting the characteristics of the wave can tell us what material it has passed through – a glimpse at Mars' interior.

Marsquakes

Mars doesn't have plate tectonics like Earth, so how does it have quakes?



Contraction
One method thought to produce marsquakes is the cooling and contraction of the planet, creating detectable seismic waves.

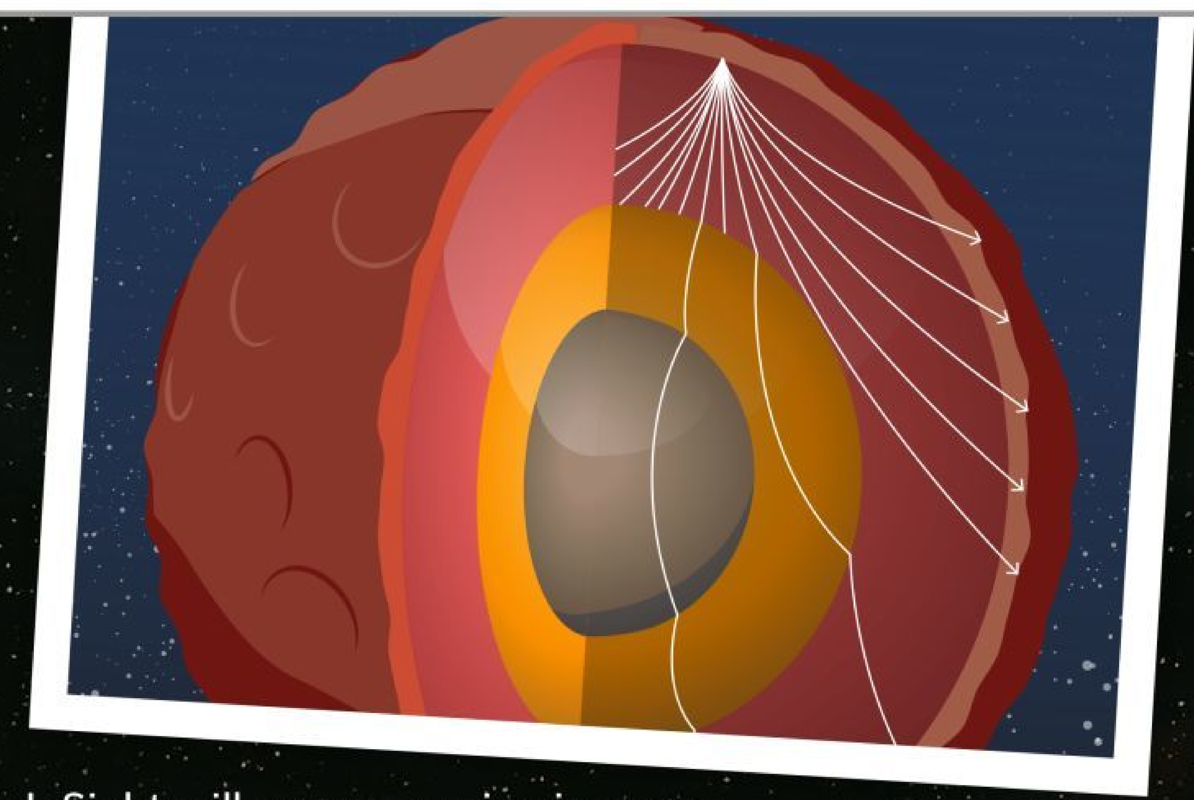


Magma
Magma coming up from the core of Mars could also be responsible for producing marsquakes and seismic waves.

Impacts
Meteorites hitting the planet could cause tremors that the super-sensitive seismometer on the SEIS instrument will pick up.

possibly partly moulten, but to find out its exact size we need to monitor it for a long time. Rovers and orbiters aren't very good at doing this as they keep moving around, but InSight will be staying in one location. It's hoped this could tell us a huge amount about the core of Mars and, in turn, tell us more about the innards of rocky planets in general.

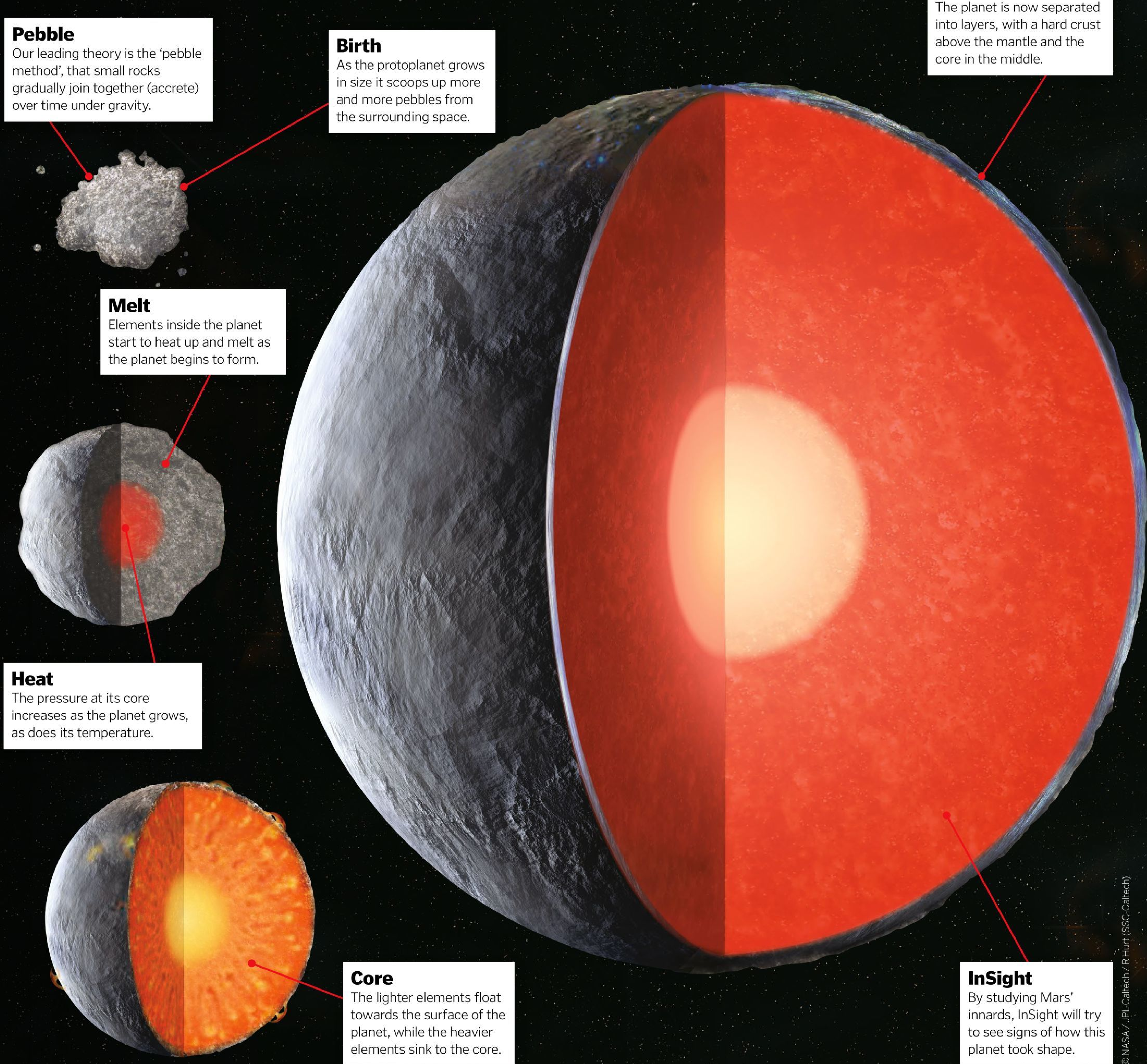
There's little doubt that InSight is, in every sense of the word, a groundbreaking mission. It will literally hammer into the ground, while simultaneously listening to the pulse of the planet and the wobble in its spin. The primary mission of the lander is expected to end on 24 November 2020, and by then we might have a whole different outlook on just how special Earth is in the universe compared to other rocky planets. Perhaps Mars was once more like us than we thought – or perhaps our planet really is one of a kind.



InSight will measure seismic waves travelling through the surface of Mars

Rocky planet formation

How we think terrestrial planets form and what InSight could add



What happens when galaxies collide?

What a cosmic pile-up will mean for the Milky Way

Astronomers already knew that our galaxy, in which our Sun is one of a 100 billion or more stars, is on a collision course with its slightly bigger neighbour, Andromeda. Now, thanks to detailed measurements of stellar motions by the Gaia space telescope, we've got a clearer idea of when the crash is due to occur: in around 4.5 billion years. That's roughly the age of the Earth, so there's no immediate cause for alarm.

Even when the collision happens, it will be a sedate affair hardly noticeable to any creatures still around in that far distant future – apart from giving them some spectacular night-sky views. In fact 'collision' is a misnomer. A galaxy is mostly empty space, so it's closer to the truth to say they 'pass through' each other. There's little chance of an individual star actually crashing into another star.

We know what happens during a galactic collision as telescopes can see them in action elsewhere in the universe. The most striking effect is on the shape of a galaxy. What started out as a neat disc or elegant spiral can be contorted beyond recognition by tidal forces. If the collision speed is slow, the two galaxies may not have enough energy to separate again, resulting in an eventual merger into a single giant galaxy. Astronomers believe that will happen with the Milky Way and Andromeda – and they've coined the name 'Milkomeda' for the future combined galaxy.

Galactic tides

As distance between galaxies gets smaller, they begin to distort each other via tidal stresses. These arise because the pull of gravity on one side of the galaxy is stronger than on the other, analogous to the way the Moon pulls more strongly on one side of the Earth. Just as the Moon raises tides by distorting the shape of the ocean, so one galaxy can alter the shape of another – on a vaster scale. Stars inside the galaxy can be flung onto completely different orbits, sometimes forming long 'tidal tails'. According to one estimate, the Sun has a small chance of ending up in such a tail, but if so, it's likely to take its retinue of planets with it, so the Solar System would survive unscathed.

The Gaia space telescope's mission is to create a map of the Milky Way

Eight billion years to Milkomeda

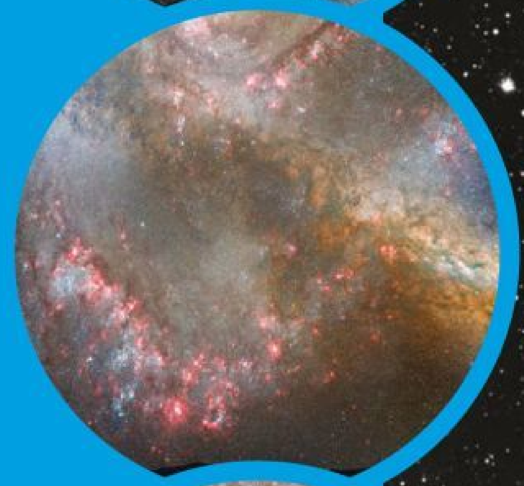
How the night sky might change as the Milky Way and Andromeda collide

Present day
The Andromeda galaxy is a faint smudge, about the size of the Moon, to the left of the Milky Way.

After 2.5 billion years
As Andromeda approaches, it becomes a much larger and brighter feature in the sky.

After 4.3 billion years
Andromeda now spans half the sky, rivalling the Milky Way in magnificence.

After 4.4 billion years
As the galaxies begin to overlap, the increased gas density generates star formation.



After 4.5 billion years
The galaxies become an amorphous mass, at the height of the collision; star formation continues.

After 4.6 billion years
As the galaxies move apart, both will show clear signs of tidal distortion, with visible tails.

After 6 billion years
After the frenzy of star formation, little gas is left as the galaxies meet for the last time.

After 8 billion years
Two become one: The the core of a newly merged giant 'elliptical' galaxy – Milkomeda.

Redshift and blueshift

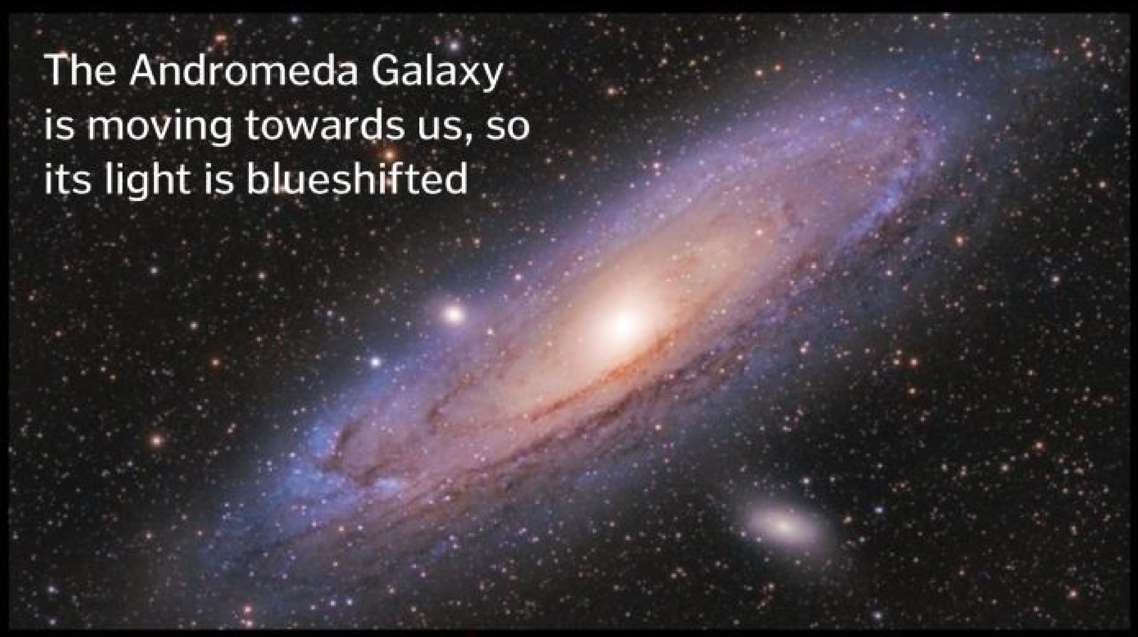
How this weird phenomenon can help us study the distant universe

If you've ever heard a police car drive by with its sirens blaring, you'll be able to understand redshift and blueshift. As the car went past you probably noticed that it sounded higher pitched as it approached you and lower pitched as it drove away. This is known as the Doppler effect, and it's caused by sound waves being pushed closer or further away from each other.

The same thing happens with light. It turns out that as a light source moves towards or away from us on a large scale, the light also gets shifted – but in this case its wavelength on the electromagnetic spectrum gets shorter or longer. Wavelength is basically an energy pattern in light that determines what colour it is. Longer wavelengths correspond to red, while shorter wavelengths correspond to blue or violet.

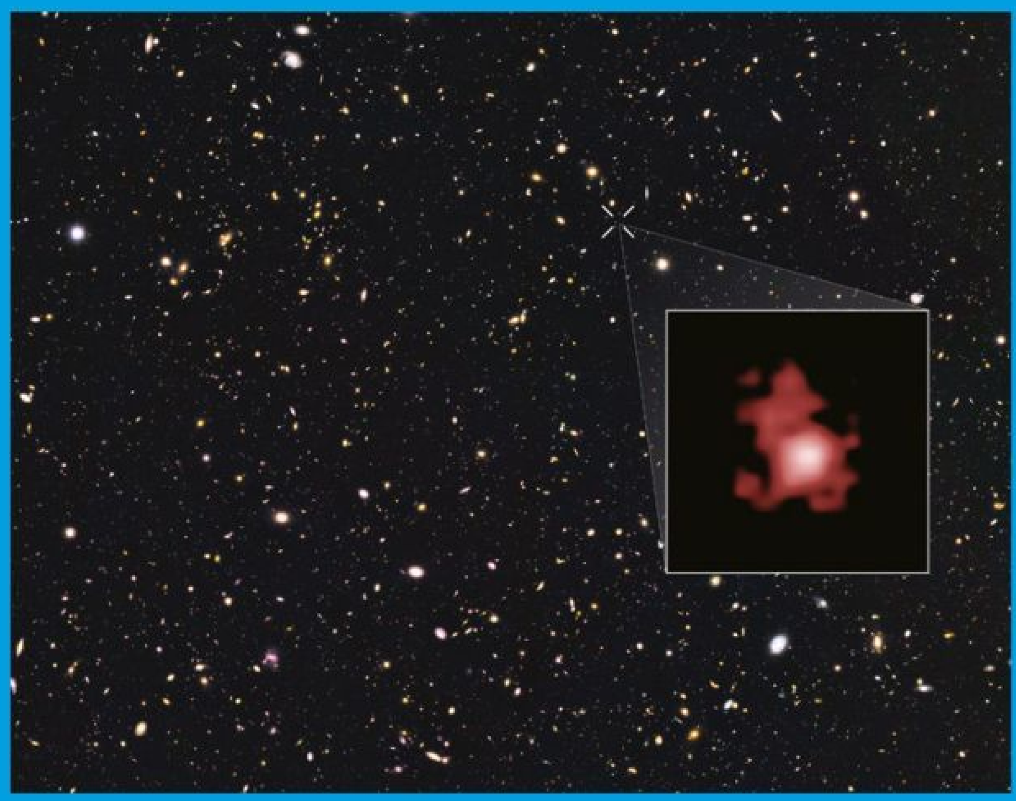
When we observe a galaxy in the universe, we find that its light is generally either redshifted or blueshifted. The former is more common, as the universe is expanding and everything is moving away from everything else. The more distant a galaxy is – and thus the faster it is moving away from us – the higher its redshift is.

A few galaxies, like the Andromeda Galaxy, are moving towards us however and are on a collision course with our Milky Way. Andromeda's light is blueshifted. Galaxies that are spinning can also exhibit a slight blue or redshift, as one side of the galaxy moves towards us while the other moves away from us.


The Andromeda Galaxy is moving towards us, so its light is blueshifted

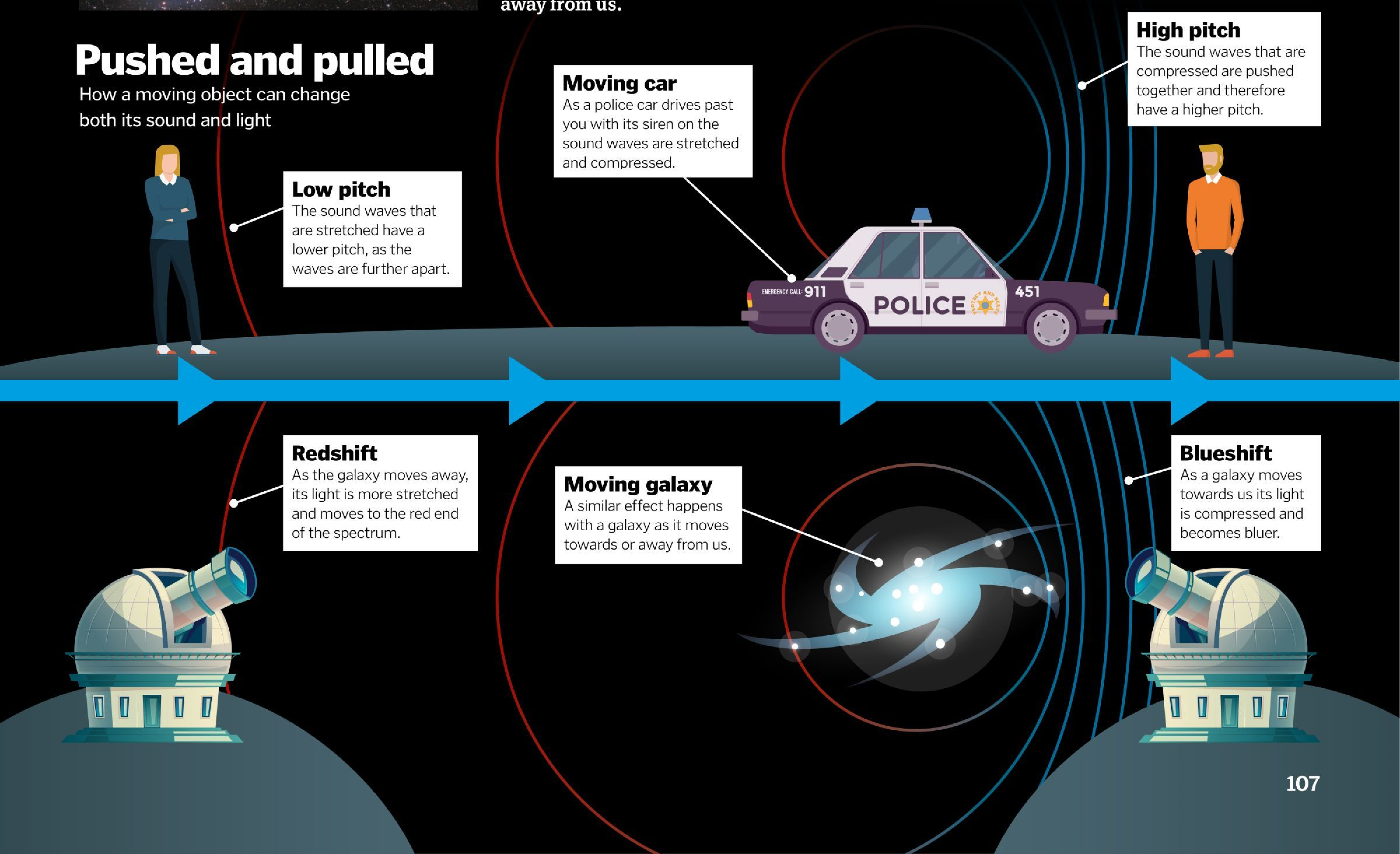
The most distant galaxy

We can use redshift to measure how far away the most distant galaxies we can see are. As a galaxy increases in speed and thus gets further away, its redshift increases. Currently, the most distant galaxy we've seen in the universe is GN-z11, which has a redshift value of 11.09. This corresponds to a distance of 13.4 billion lightyears in terms of how far the light has travelled to reach us across the universe. This also means we are looking far back in time, to just 400 million years after the Big Bang. Astronomers are now hoping to look even further back towards the Big Bang itself to find some of the first galaxies that formed in the universe.


The bright infant galaxy GN-z11 is located in the direction of the Ursa Major constellation

Pushed and pulled

How a moving object can change both its sound and light



IMPACT EARTH!

How massive meteorites have shaped our planet for better and for worse

Words by **Jonathan O'Callaghan**

Earth sure hasn't had it easy. Throughout its life our planet has been repeatedly hit, pummelled and even shattered by incoming space rocks, at times wiping out vast swathes of life and significantly changing our planet's habitability. But these mega impacts haven't just caused mass extinctions; they've also been responsible for allowing life to thrive here in the first place, and our very own Moon may owe its existence to a colossal impact long ago.

Our Solar System is full of asteroids and comets, pieces of debris left over from the Sun's infancy that failed to form into planets. Some of these orbit close to Earth and are known as near-Earth asteroids, the ones that make the closest passes to our world. The majority of asteroids in our Solar System can be found in the asteroid belt between Mars and Jupiter, home to millions of asteroids, with the largest being Vesta, which has a mean diameter of 530 kilometres. Farther out in the Solar System you'll find Trojan asteroids, which share orbits with the larger planets, and in the outer Solar System, the Kuiper Belt and beyond you'll find pieces of icy rock. Occasionally, a comet from out here makes its way towards Earth.

If one of these rocks gets set on a collision course with Earth the consequences for us can be dire. Most debris from the Solar System simply burns up in our atmosphere and causes us few problems, becoming what's called a meteor. If they're big enough, however, they can make it to the surface in the form of a meteorite. And the bigger a meteorite is, the bigger an impact it'll have on our planet. We measure the impact an asteroid could have on

"OUR PLANET HAS BEEN REPEATEDLY HIT BY SPACE ROCKS"

Professor Kurt Kjær collecting a sample from the newly discovered Hiawatha Crater in Greenland

our planet using the Torino Scale, which ranges from 0 to 10. An object at the lower end has less chance of an impact and poses few dangers to life on Earth. At the upper end an impact is a near certainty, and the prospects for life surviving are slim. Fortunately, we know of no objects above a zero on the scale at the moment.

In the past, of course, we have indeed been hit by such objects, although long before modern humans were around. Most of these impacts leave noticeable scars on our surface in the form of craters. For impacts that happened long ago, these craters can be hidden beneath new land, requiring us to dig underground or search underwater for remnants of them. For the most part, with our detailed satellite imagery of the planet, we've done a pretty good job of finding most of the noticeable craters.

In November 2018, scientists announced the discovery of a huge new crater hiding beneath the Greenland ice sheet. Called the Hiawatha Crater, this mammoth depression measures 31 kilometres across, making it one of the 25 largest impact craters on Earth. This is not only the biggest new crater discovered in recent history but the first crater we have ever found under an ice sheet. Its existence suggests there could be many more discoveries to come.

This crater was found by flying over Greenland and using ice-penetrating radar to peer below the ice. Scientists use this technique to monitor the effects of climate change and see how much ice is melting. They were surprised to discover something else too. As the ice continues to melt and the landscape changes it is revealing previously undiscovered features – including a huge impact crater. Once the team had spotted what looked like a hidden crater they began to optimise and enhance the available data to see if they could get a better picture of it. This included taking further radar images in May 2016 in an attempt to create a clearer picture of what was under the ice. These results showed their initial assumption had been correct – there was a larger crater with a rim around it.

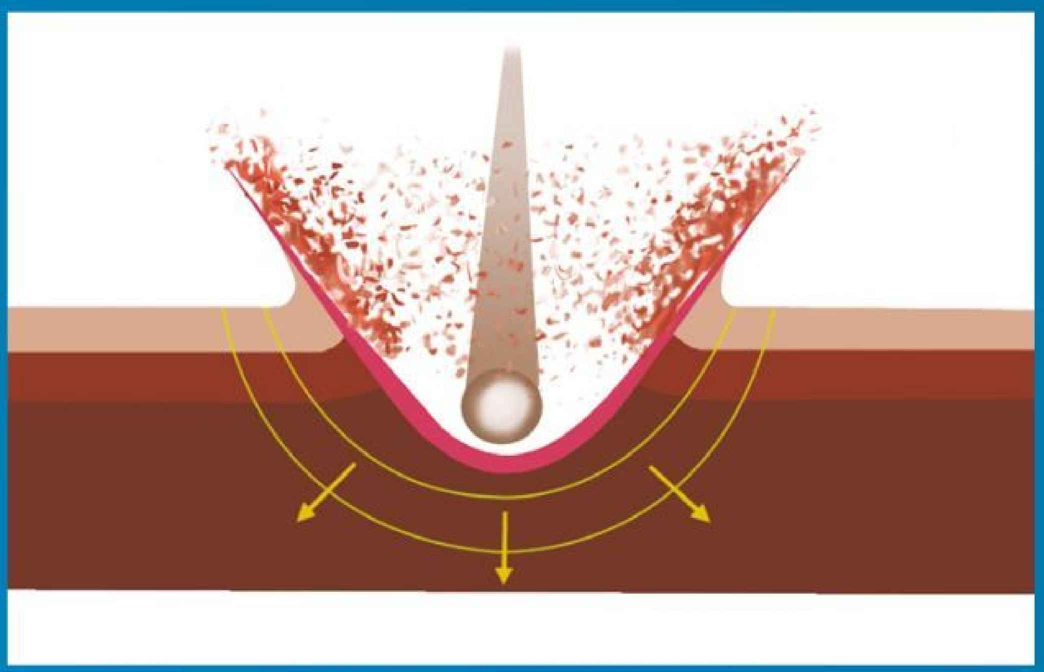
> "HOW DID ONE SO BIG MANAGE TO AVOID OUR DETECTION?"

To find out what might have caused the crater, Professor Kurt Kjær from the Natural History Museum of Denmark – who led the project – travelled to the site in July 2016 to collect samples. The crater is buried several kilometres below the ice, so it is not possible to directly sample it, but Professor Kjær found that part of the glacier that housed the crater was melting, meaning meltwater containing minerals from the crater was seeping out. He collected samples of this water and found the smoking gun that pointed to an asteroid impact. The meltwater contained quartz grains that had been shocked, most likely by an impact.

It is thought that this crater was caused by an iron asteroid measuring about 1.5 kilometres across striking the Earth's surface at a velocity of 20 kilometres per second. This would give it an impact force large enough to have caused this

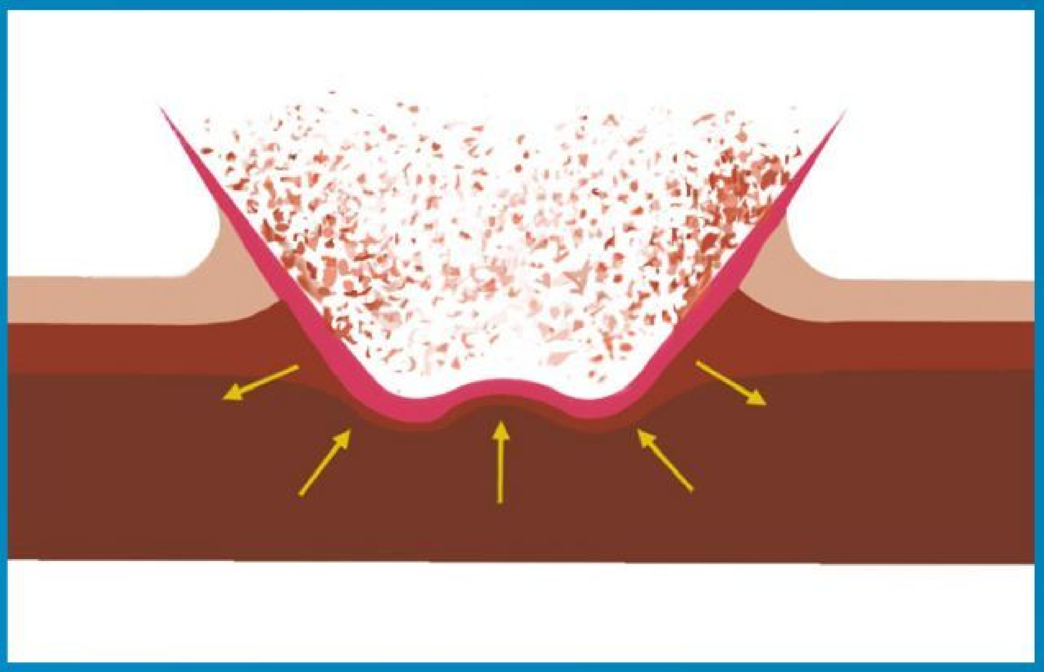
Making a big impression

How the classic crater formation is created by large impacts



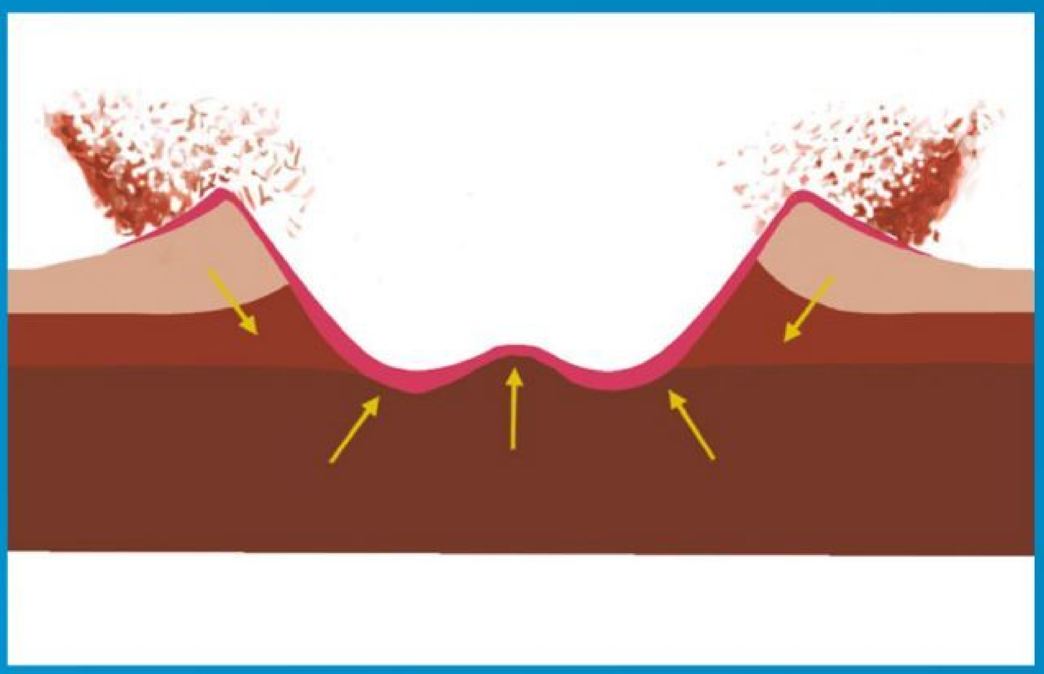
Smashing the surface

Complex craters are formed by large impacts, tending to be wider across but shallower in depth (compared to their diameter) than simple craters formed by smaller impacts.



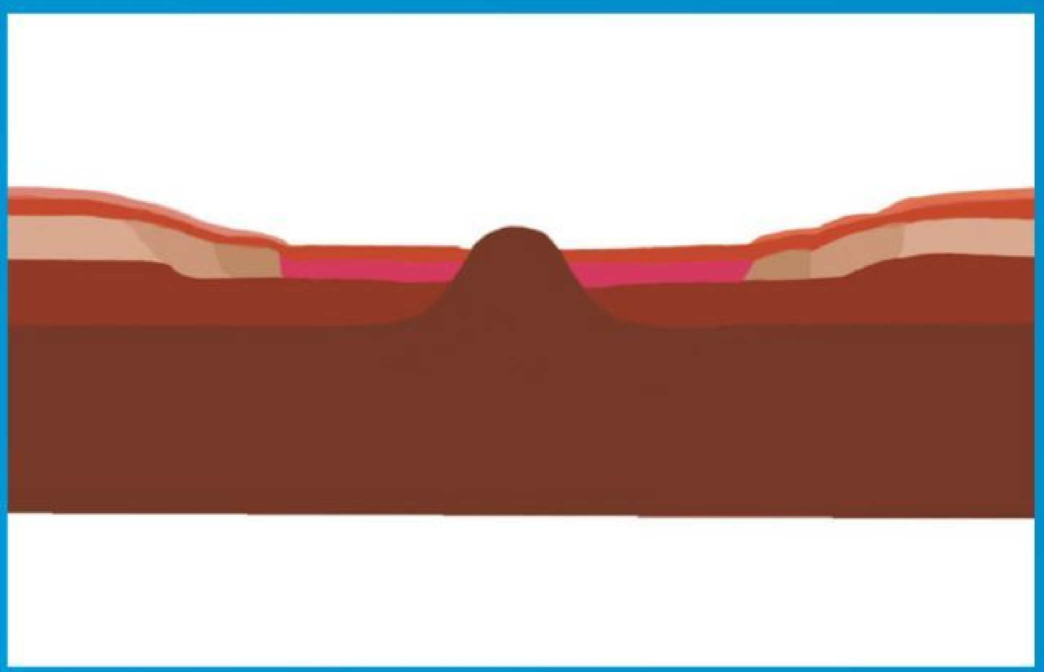
Crater walls

The force of the impact causes the walls to collapse downwards, adding debris to the interior of the crater and decreasing its depth.



Central peak

Complex craters also have a hump in the middle, where material has rebounded from the impact to form a shallower mound that protrudes upwards.



Final diameter

On Earth, complex craters tend to be more than four kilometres in diameter. On different planets, gravity has a significant effect on the type of crater formed.

The Hiawatha Crater is believed to have been caused by a huge rock rich in iron

Impact events may have caused multiple extinction events on Earth

huge crater beneath the ice sheet. The next largest impact crater is the Tookoonooka crater in Australia, which measures 66 kilometres across. But both pale in comparison to the biggest impact crater found on Earth to date, the Vredefort Crater in South Africa, which has a whopping 300-kilometre diameter.

Most of these larger craters were discovered long ago, so how did one so big manage to avoid our detection for so long? The answer mostly lies in our ability to map below the surface. While we have satellite imagery of pretty much the whole planet, peering beneath the surface is a bit more difficult. But with more and more radar-equipped planes flying over the ice sheets, we're now able to more easily look below this ice to monitor climate change. In so doing we're also able to make fascinating discoveries like this. There may well be more such discoveries awaiting us under the ice.

The Hiawatha Crater is not a closed case just yet though. One of the biggest unanswered questions about this impact is when it took place. The team currently think it occurred anywhere from between 12,000 to 3 million years ago, making it our most recent impact by far – the last major meteorite event before this occurred about 40 million years ago. We know that large impacts like these can have a profound effect on life on our planet, so is it possible the Hiawatha Crater heralds an extinction event?

Scientists have previously struggled to explain the sudden mass extinction of many species that began about 12,900 years ago, called the Younger Dryas. This led to the death of many large animals known as megafauna, while an early human society known as the Clovis people disappeared completely from the archaeological record. Some have suggested a cooling effect on the planet took place, but the reasons aren't

Q&A

Professor Kurt Kjær, Natural History Museum of Denmark

The lead author of the paper published in *Science Advances* talks about the discovery of the Hiawatha Crater

Why was this discovery so exciting?

How often do you find a new, well-preserved impact crater on Earth that is so obvious when you see it? I think it's super exciting because we have thousands of satellites orbiting Earth, we have planes flying everywhere, we record everything that happens on Earth's surface. To discover a thing like this, despite all of these things, in this age where we can see everything from a satellite, it really is a true discovery. You don't have the opportunity as scientists to do that very often.

Why had we not seen this crater before?

Our knowledge of the topography beneath the Greenland ice sheet is getting better and better all the time. Operation IceBridge from NASA has done a great job of doing this, because they map the ice sheets themselves and also map the base of the ice sheets with ice-penetrating radar. A new hidden landscape has started to emerge.

Do we have an idea of when it happened?

When it came out, a lot of people threw themselves on the Younger Dryas hypothesis. We do not do that in the paper. We say we cannot confirm if that is the case, but we cannot reject that hypothesis either. So it might be young – 11,700 years old – very young. And there's some indication [that's the case] due to how it's shaped, how well preserved it is.

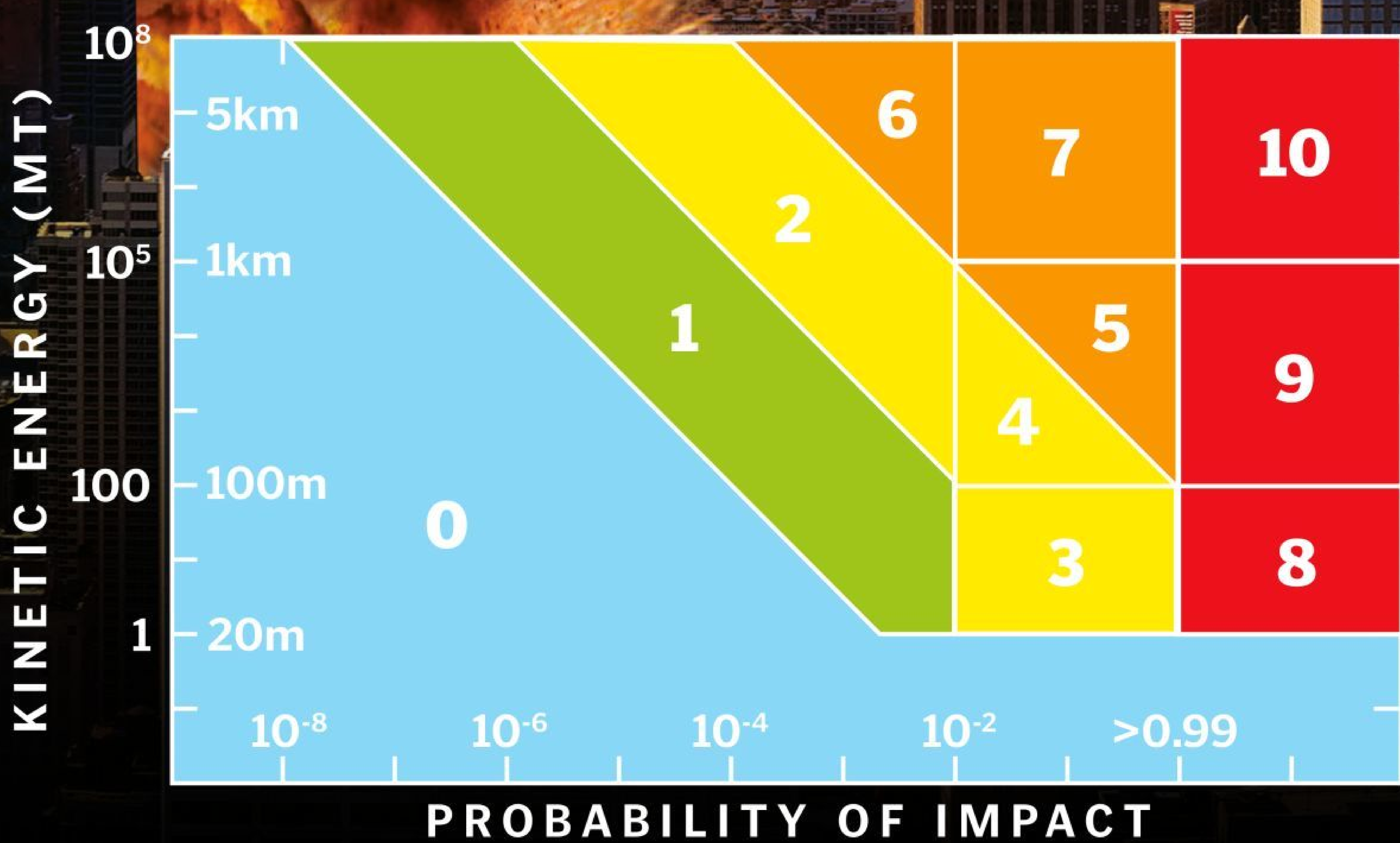
Meteors burn up in our atmosphere, whereas meteorites reach the surface

Asteroids, meteors, meteorites and comets

An asteroid is a piece of rocky debris left over from the formation of our Solar System that continues to orbit the Sun. Comets are similar, but they formed farther out in the Solar System and are thus likely to have considerably more ice than asteroids, as well as distinctive 'tails' of material. A meteor is an asteroid that enters our atmosphere but burns up, sometimes appearing as a shooting star. They are typically quite small and do not reach the surface. A meteorite is an asteroid or comet that does reach the surface and can be anything from a small rock to a huge crater-forming leviathan.

The Torino Scale

The Torino Scale is a way for us to rank how dangerous a potential impact with Earth could be. The scale ranges from 0 to 10 and is used by scientists to inform the public about the impending danger of an asteroid. The lowest ratings refer to objects that are either unlikely to hit us or are so small that they will simply burn up in our atmosphere. Those in the mid ranges refer to objects that are expected to come close to our planet so have a chance of hitting and are big enough that they could cause a considerable amount of damage. The upper end of the scale is reserved for objects that are certain to hit us and are so large that they could threaten life on our planet. Fortunately, at the moment we know of no objects that are above a 0 on the scale.



BLUE
There is essentially zero chance of a collision, or the object is too small to cause us any danger.

GREEN
The chance of a collision is very unlikely, so there is little cause for concern.

YELLOW
There is a one per cent or greater chance of an impact, which could cause localised destruction.

ORANGE
A very close encounter is predicted within decades, and governments may need to prepare for an impact.

RED
A collision with our planet is a certainty, and the object could threaten our civilisation on Earth.

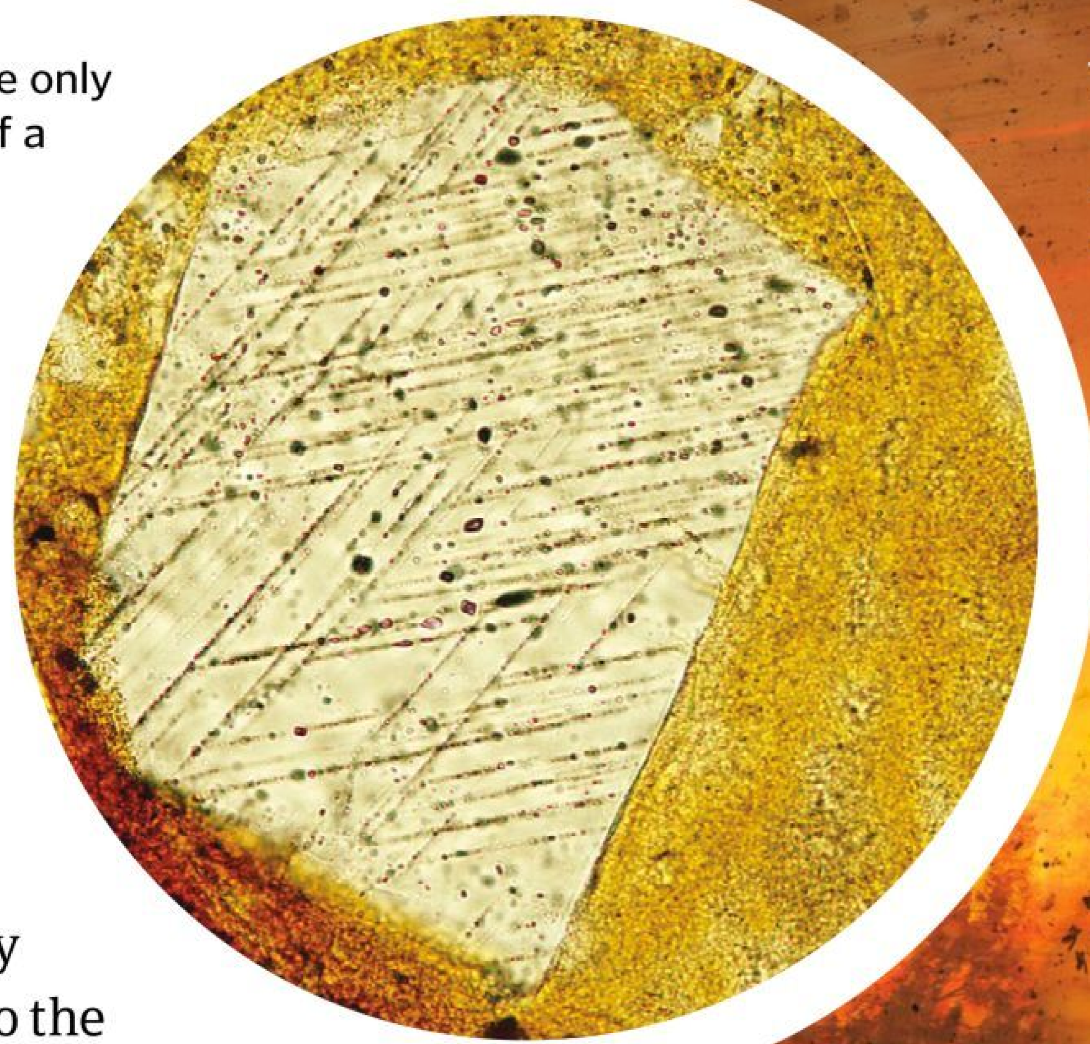
completely clear. A possible explanation is that a large impact caused the planet to cool – the Hiawatha Crater may be evidence of this.

Looking far back into Earth's history we know that other meteorites have played a major part in our planet's evolution. Right back to the birth of our planet, 4.54 billion years ago, we think that meteorites were repeatedly slamming into the surface. Asteroids and comets are both rich in water, so a popular hypothesis is that these rocks were responsible for actually bringing the initial water to the Earth. We have also discovered that some space rocks are also rich in the ingredients of life, known as 'organics'. So life on Earth might have originated in a monumental impact long ago.

"WE SEE CRATERS ALL OVER THE PLACE"

Then there's the Moon. Studying samples returned by the Apollo missions in the 1960s and 1970s, scientists were surprised to learn that Earth and its satellite shared similar chemical signatures. This led scientists to consider that the Moon may actually be a piece of Earth itself. This is known as the giant-impact hypothesis. The idea is that a large object dubbed Theia, possibly the size of Mars, slammed into our planet about 4.5 billion years ago. This colossal impact ejected a huge amount of debris into Earth orbit that, over time, gradually coalesced into the Moon. Some questions remain, however, including how our planet would have actually survived such an impact. But at the moment this is the best theory we have to explain how the Moon formed, and it all started with a massive bang.

We are pretty sure that throughout Earth's history other, smaller impacts also had major effects on life. One of the most famous such events was the Chicxulub impact about 66 million years ago. A huge crater 180 kilometres wide in the Gulf of Mexico, it points to a large impact from an asteroid or comet up to 15 kilometres across, with a faint trace of this crater remaining today. A drilling project took place to try and directly sample this crater after it had been discovered in the 1990s. This event is thought to have brought to an end the



These scars of shocked quartz are only created by a shock on the scale of a meteor impact

The dinosaurs (along with many other species) were wiped out by mega impact

Cretaceous period on Earth, with 75 per cent of life – including most of the dinosaurs – wiped out as a result of a chain of global catastrophes triggered by the impact.

Earth, of course, is not the only world in our Solar System that's been shaped by impacts. Our Moon is home to the South Pole-Aitken Basin, a vast crater roughly 2,500 kilometres in diameter. Another on Mars – called Utopia and measuring 3,300 kilometres across – is thought to be the largest of all. Throughout history each planet has been bombarded by objects, so Earth is no exception.

While the prospect of an asteroid hitting Earth might be terrifying – and there is plenty of evidence such events are catastrophic – we may very well owe our own beginnings to space rocks crashing into Earth. Thankfully, we know of no asteroid on a path with Earth that could result in another large impact event, but it's likely we will face such a prospect in future.

Studying the history of our planet and finding new craters like the Hiawatha Crater is vital to working out what effect these impacts have on our planet and what our prospects of surviving long into the future are. The very existence of life on Earth may one day rely on the scientists who examine the devastation of the past.

Meteor Crater in Arizona is one of the world's best-preserved meteorite craters

10%

of known near-Earth asteroids are PHAs (potentially hazardous objects)

IN 2010, HUBBLE SAW THE AFTERMATH OF TWO ASTEROIDS COLLIDING

ESA's Hera mission aims to reach a binary asteroid in the 2020s

2,000 years

Average passage of time before a football pitch-sized meteorite hits Earth

25 metres

Smallest size for an asteroid to pass through Earth's atmosphere

Asteroids in similar orbits typically came from the same parent

1km

Minimum meteorite size for disastrous worldwide effects

SOME ASTEROIDS ARE RICH IN USEFUL METALS LIKE PLATINUM

10 BIGGEST IMPACTS ON EARTH

The largest craters that can be found on the surface of our planet

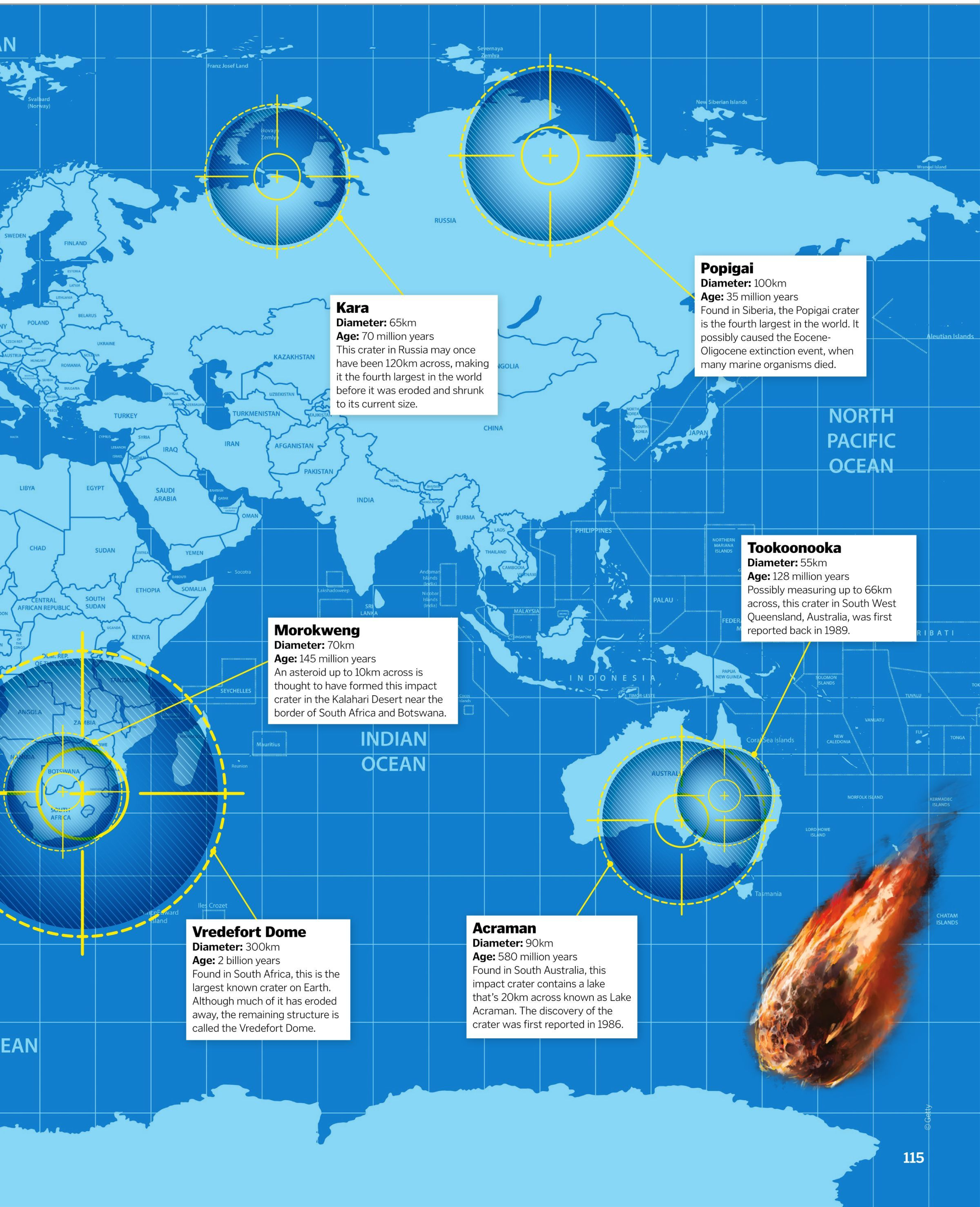
Beaverhead
Diameter: 60km
Age: 600 million years
On the border of the US states of Montana and Idaho you'll find this crater. The only remaining visible evidence for this crater comes from rock that was shocked by the impact force.

Sudbury Basin
Diameter: 130km
Age: 1.8 billion years
The third largest impact crater is the Sudbury Basin in Ontario, Canada, thought to have been caused by a meteorite up to 15km across.

Manicouagan
Diameter: 100km
Age: 215 million years
This ring-like lake found in Quebec, Canada, is thought to have been formed by a meteorite about 5km across hitting Earth.

Chicxulub
Diameter: 180km
Age: 66 million years
Believed to have wiped out the dinosaurs, the Chicxulub crater on the Yucatán Peninsula in New Mexico is the second largest impact crater on Earth.

DID YOU KNOW? *The only person to ever be hit by a meteorite in recorded history was Ann Hodges from Alabama in 1954*



Kara
Diameter: 65km
Age: 70 million years
This crater in Russia may once have been 120km across, making it the fourth largest in the world before it was eroded and shrunk to its current size.

Popigai
Diameter: 100km
Age: 35 million years
Found in Siberia, the Popigai crater is the fourth largest in the world. It possibly caused the Eocene-Oligocene extinction event, when many marine organisms died.

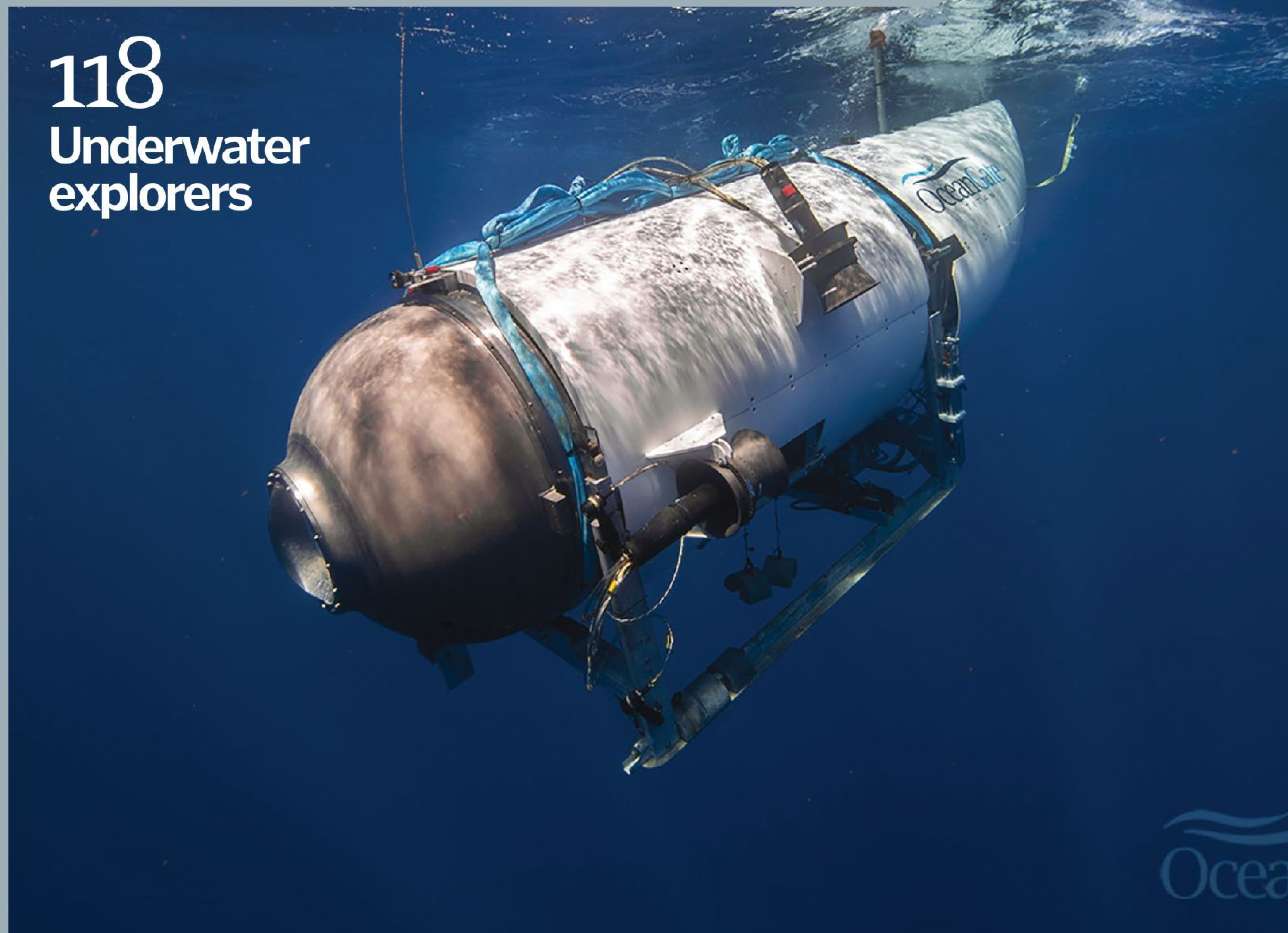
Tookoonooka
Diameter: 55km
Age: 128 million years
Possibly measuring up to 66km across, this crater in South West Queensland, Australia, was first reported back in 1989.

Morokweng
Diameter: 70km
Age: 145 million years
An asteroid up to 10km across is thought to have formed this impact crater in the Kalahari Desert near the border of South Africa and Botswana.

Vredefort Dome
Diameter: 300km
Age: 2 billion years
Found in South Africa, this is the largest known crater on Earth. Although much of it has eroded away, the remaining structure is called the Vredefort Dome.

Acraman
Diameter: 90km
Age: 580 million years
Found in South Australia, this impact crater contains a lake that's 20km across known as Lake Acraman. The discovery of the crater was first reported in 1986.

TRANSPORT



122
Super-sucking trucks

123
Lotus ice mobile

UNDERWATER EXPLORERS

Welcome aboard! Prepare to dive into the world of the private submersibles taking us to incredible new depths of the ocean

Words by **James Horton**

The oceans serve as Earth's largest habitat and are home to a phenomenal array of life. As well as discovering this rich diversity, exploring the depths allows us to peel back the curtain on another world.

Mere centimetres beneath the waves corals bloom, fish graze, cephalopods hunt and crustaceans battle. But few of us ever get the opportunity to venture deeper, down where the pressure is too much for our unprotected bodies to endure and the light fades away, leaving the water an inky black. At these extreme depths fantastical creatures begin to appear. First the swordfish, then the angler fish, then for the lucky few, the elusive giant squid. Until recently a private citizen could do little but dream about seeing such sights for themselves. But there are now some astounding vehicles that have unlocked the potential of the deep blue. We are in the era of the private submersible, which not only lets civilians peruse the depths at their leisure, but lets them do it in style.

These manned vehicles are escorted to their dive sites by other vessels, but once set loose under the water they are able to roam independently. Many of the companies that are selling such technologies also offer pilot training, meaning the private operator can take full control of their new vehicle. The variety already on offer is astounding. In this feature we'll uncover shallow pleasure cruisers, hardier research vessels and even a submersible that can reach the very deepest point on the ocean floor. Yes, that's right: you can now buy a vehicle that will allow you to replicate a feat that has so far only been achieved by three people in history. So read on and get saving, because these pleasures don't come cheap. But it'd be hard to argue that they aren't worth the money.

> *"At these extreme depths fantastical creatures begin to appear"*

Bottom dweller

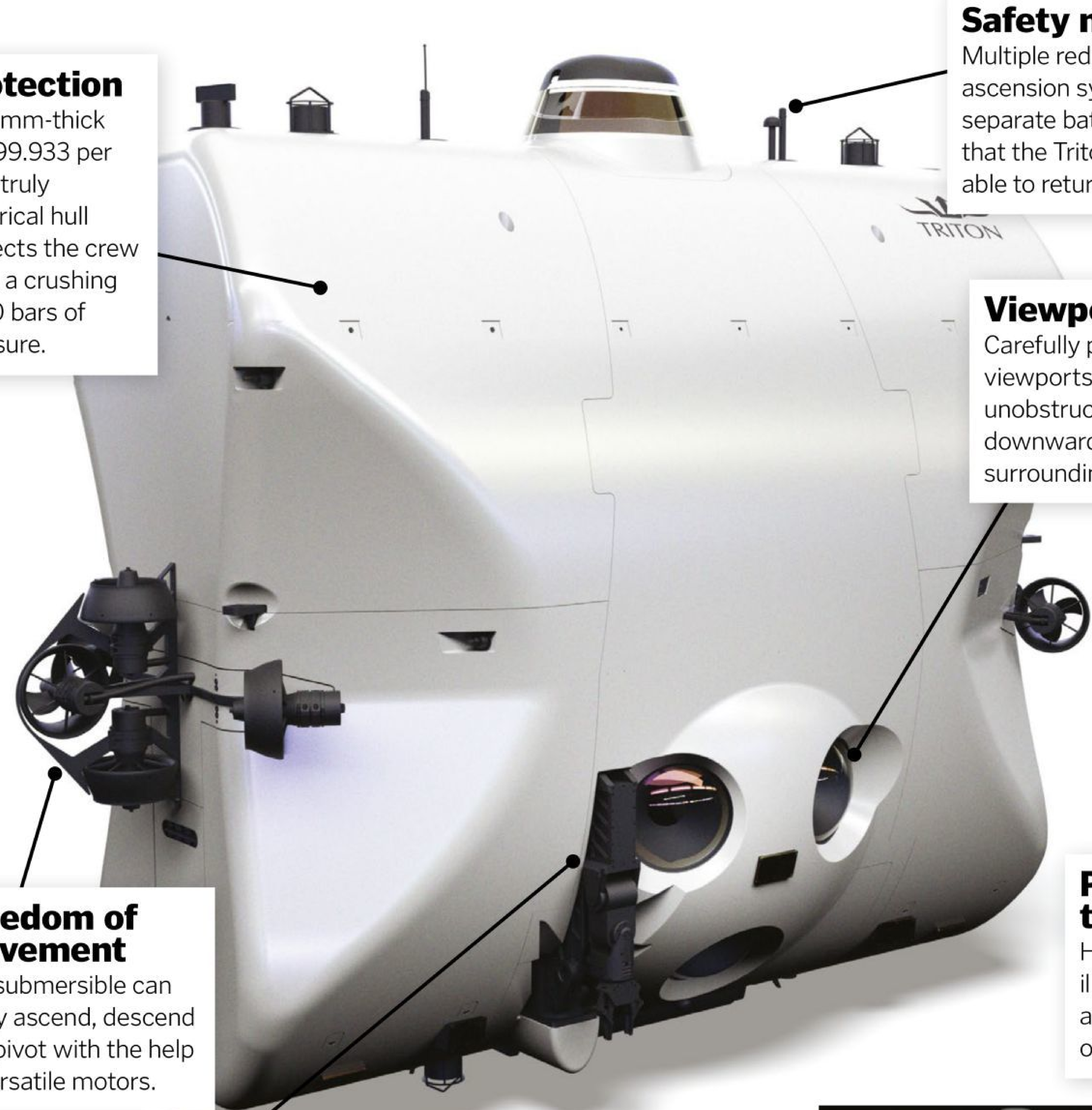
Meet the Triton 36000/2, an emerging veteran of the deep

The latest trialled and tested Triton model is a juggernaut of a submersible. Built to endure the punishing pressures of the oceans depths repeated times, the vehicle is currently undergoing a pilgrimage to prove its mettle.

Under the control of a private owner, Triton is touring the world on a quest to escort its pilot to the deepest point of the world's five oceans. As the sole manned submersible of the Five Deeps Expedition, at the time of writing Triton has already touched down at the bottom of the Atlantic, Southern and Indian oceans, and it will tackle the Pacific and Arctic depths later this year. Upon its completion of this record-breaking mission the submersible, its launch vessel and accompanying craft will become available to a private owner. They can all be yours for just $48.7 million (around £37.7 million).

TRITON 36000/2

DEPTH RATING:
11,000m
MAX CREW:
2
LIFE SUPPORT (HRS):
16 (standard)
96 (emergency)
MAX SPEED:
3kn



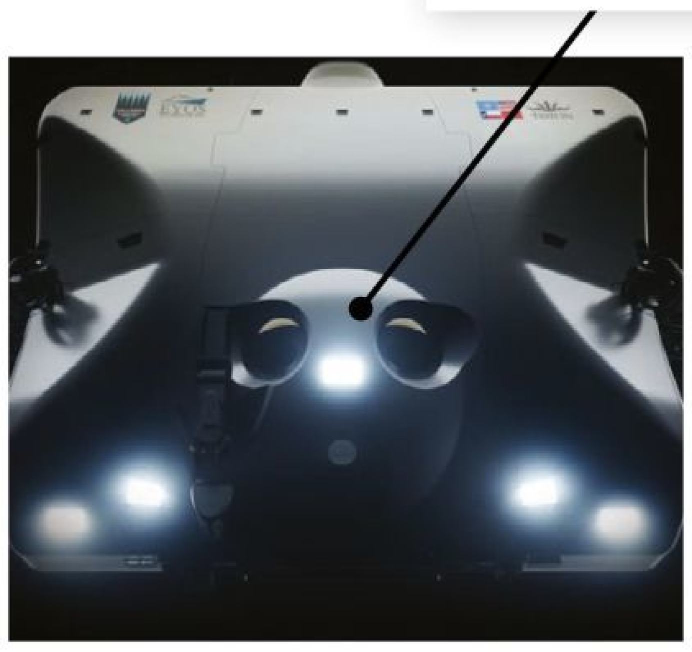
Protection
A 90mm-thick and 99.933 per cent truly spherical hull protects the crew from a crushing 1,100 bars of pressure.

Safety measures
Multiple redundant ascension systems and 12 separate batteries ensure that the Triton will always be able to return to the surface.

Viewports
Carefully positioned acrylic viewports allow the crew unobstructed forward and downward views of their surroundings.

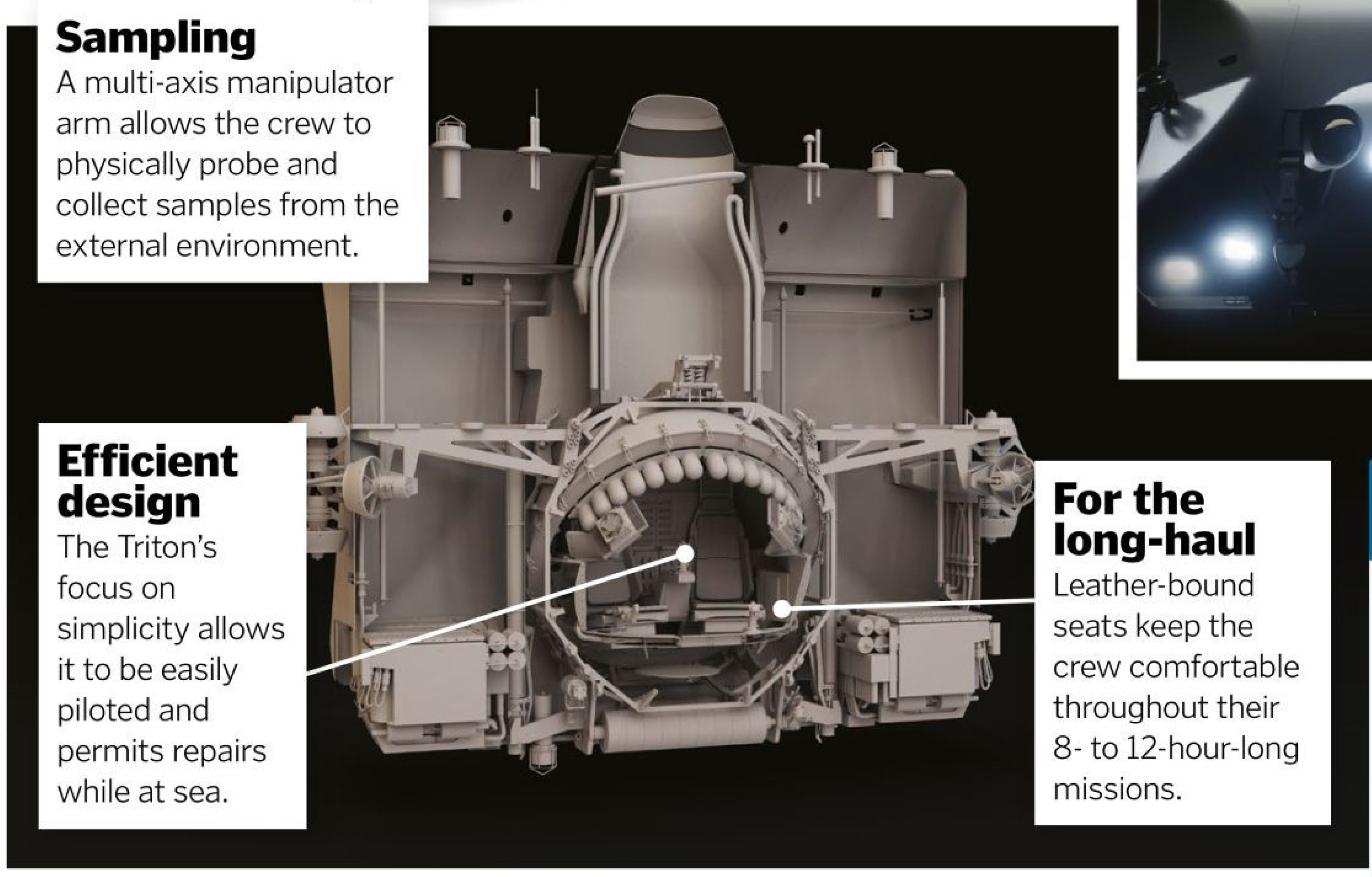
Freedom of movement
The submersible can easily ascend, descend and pivot with the help of versatile motors.

Piercing the dark
High-output LEDs illuminate the absolute darkness of the ocean floor.



© Triton Sub

Sampling
A multi-axis manipulator arm allows the crew to physically probe and collect samples from the external environment.



Efficient design
The Triton's focus on simplicity allows it to be easily piloted and permits repairs while at sea.

For the long-haul
Leather-bound seats keep the crew comfortable throughout their 8- to 12-hour-long missions.

Record-breaker

In March 2012, film-maker James Cameron touched down at the deepest point in the world's ocean – near the very bottom of the Mariana Trench. Just two others had achieved the feat before, and Cameron was the first pilot to make the descent solo. Cameron was housed in the state-of-the-art Deepsea Challenger submersible, which was able to capture valuable data. The vehicle itself was an engineering marvel, requiring the team to invent a new composite of foam – to help the vehicle ascend – and develop novel fluid-compensated electronics to produce working thrusters. Equipped with a robotic arm, a 2.5-metre tower of LEDs, two robotic vehicles and 3D cameras, Challenger was able to bring a heap of material back to the surface. The mission was a resounding success.

Titanic and *Avatar* film director James Cameron piloted the Deepsea Challenger in 2012

© Getty

Ocean tourer

Dubbed an 'underwater lounge', the Aurora 6 boasts two recliners positioned behind the pilot's chair, a guest area seating three more behind that, and even a lavatory at the rear. Passengers get near-complete views of their environment from inside acrylic globes that form the protective hull. As the vessel tours the ocean, its occupants are treated to an immersive experience akin to an underwater glass tunnel you could find at an aquarium. Except the Aurora can dive to 1,000 metres and explore the darkened depths below.

The Aurora 6 is designed to offer five passengers tantalising views in blissful comfort

© Seamagine

SEAMAGINE AURORA 6

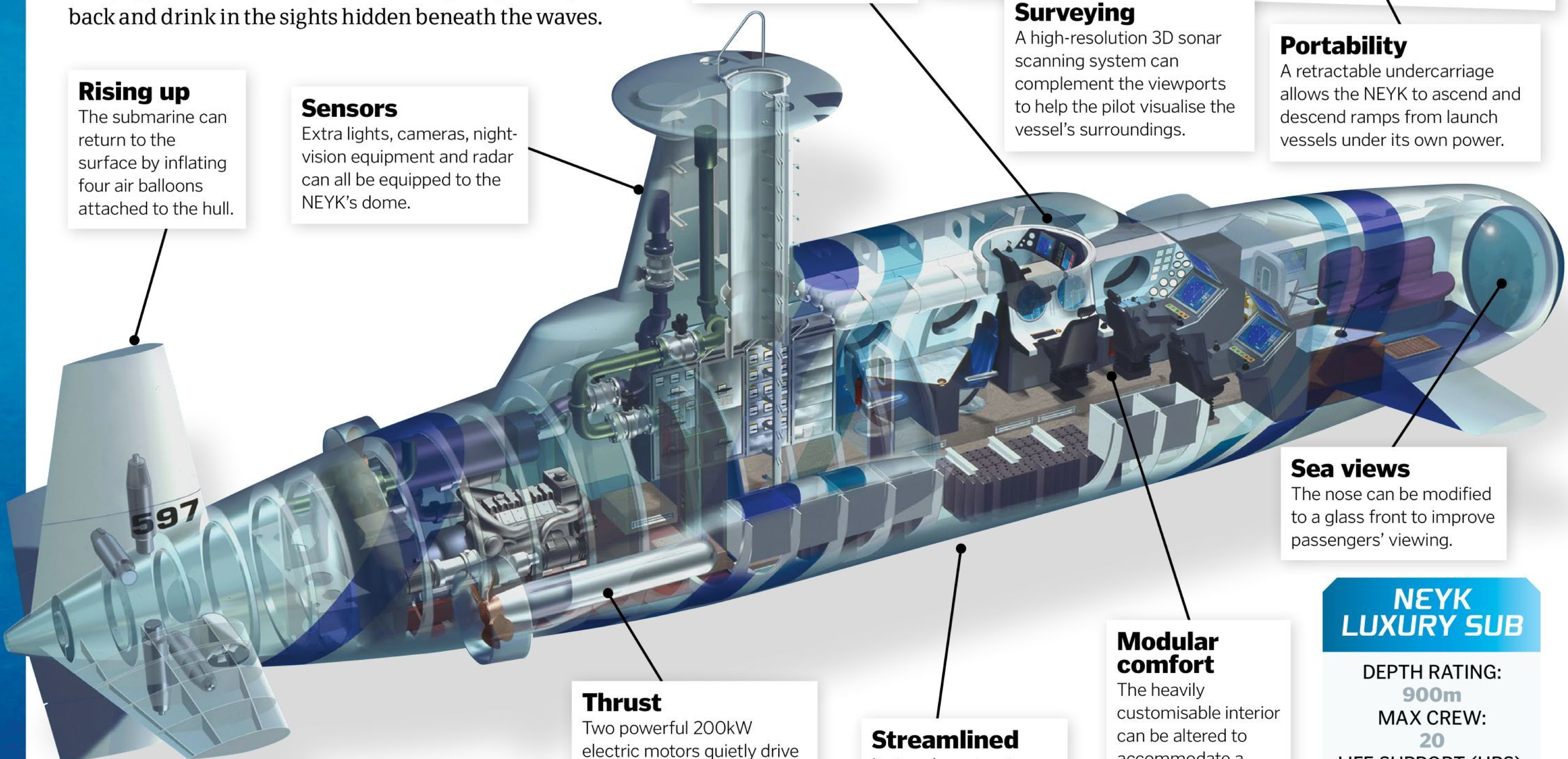
DEPTH RATING:
1,000m
MAX CREW:
6
LIFE SUPPORT (HRS):
8 (standard)
96 (emergency)
MAX SPEED:
3kn

Underwater luxury

Cruise along in unrivalled splendour beneath the ocean tides

Enjoy all mod cons while exploring underwater

Sometimes a massive yacht just isn't enough. For those fortunate few who are lucky enough to tour the seas on their own private vessels, a pleasure cruise beneath the waves undoubtedly holds as much appeal as the sights to see above it. Fortunately, the NEYK submarine is ready and able to fill this purpose. With a modular design that can be easily modified to fit its owner's specifications and desires, the NEYK can host a crew of up to 20 people. The airplane-style hull is also peppered with viewports, allowing the passengers to sit back and drink in the sights hidden beneath the waves.



360° vision
The pilot can gain a wide view via the top viewport.

Surveying
A high-resolution 3D sonar scanning system can complement the viewports to help the pilot visualise the vessel's surroundings.

Portability
A retractable undercarriage allows the NEYK to ascend and descend ramps from launch vessels under its own power.

Rising up
The submarine can return to the surface by inflating four air balloons attached to the hull.

Sensors
Extra lights, cameras, night-vision equipment and radar can all be equipped to the NEYK's dome.

Sea views
The nose can be modified to a glass front to improve passengers' viewing.

Thrust
Two powerful 200kW electric motors quietly drive the propellers, providing the crew with a tranquil cruise.

Streamlined
Its teardrop structure helps the slender vessel surge through the water at up to 15kn.

Modular comfort
The heavily customisable interior can be altered to accommodate a large crew, additional furniture or extra equipment.

NEYK LUXURY SUB

DEPTH RATING:
900m
MAX CREW:
20
LIFE SUPPORT (HRS):
125
(12 passengers)
MAX SPEED:
15kn
(11kn surfaced)

TRITON 1000/2

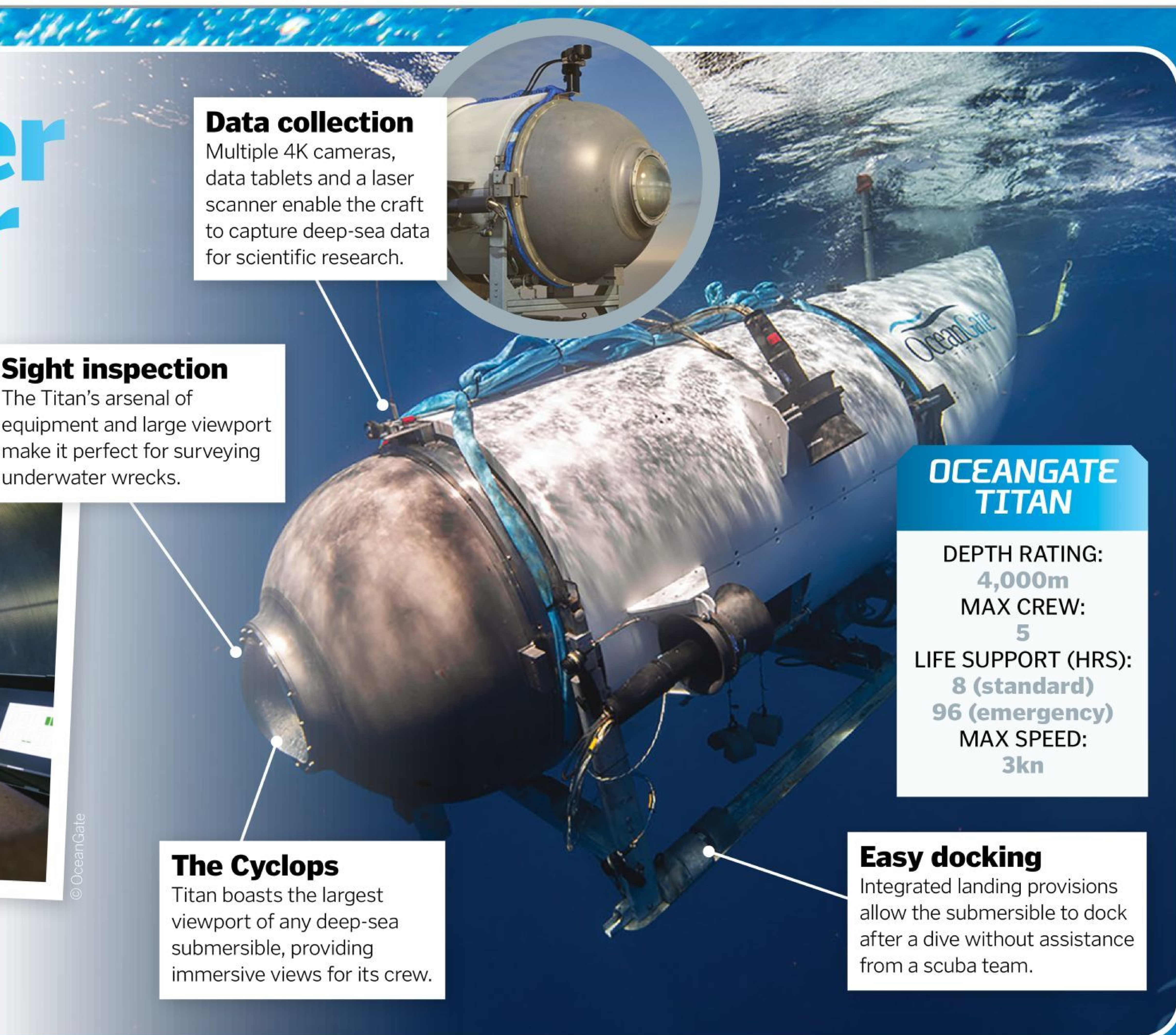
DEPTH RATING:
305m
MAX CREW:
2
LIFE SUPPORT (HRS):
10
MAX SPEED:
3kn

Shallow dive

You needn't travel far underwater to enjoy the splendour of marine life. As any keen snorkeler or scuba diver could testify, the bustling marine cities of coral reefs and the diverse array of predators and prey that swarm the shallows offer some truly mesmerising sights. Triton's adventure sub, the 1000/2 model, facilitates long stays at these enchanting locations for a pilot and their passenger. Equipped to easily plummet through the shallows, the vessel can playfully scour coastal waters from dawn until dusk. For the media-minded, the vehicle can also tolerate a hefty payload of cameras for capturing the marine environment and footage of sunken wrecks. A mechanical arm mounted on its front also enables the crew to interact with their surroundings and gather samples to bring back to the surface.

Deep-water researcher

The Titan is an innovative deep-sea science vessel



Data collection
Multiple 4K cameras, data tablets and a laser scanner enable the craft to capture deep-sea data for scientific research.

Sight inspection
The Titan's arsenal of equipment and large viewport make it perfect for surveying underwater wrecks.

The Cyclops
Titan boasts the largest viewport of any deep-sea submersible, providing immersive views for its crew.

Easy docking
Integrated landing provisions allow the submersible to dock after a dive without assistance from a scuba team.

OCEANGATE TITAN

DEPTH RATING: **4,000m**
MAX CREW: **5**
LIFE SUPPORT (HRS): **8 (standard)** **96 (emergency)**
MAX SPEED: **3kn**

Sports sub

No matter the hobby, there are always those who seek to take it to a greater extreme. Enter the HiPer Sub 2, a retro-looking submersible that resembles a sports car turned amphibian vehicle straight out of a classic James Bond movie.

The vessel can travel at a respectable six knots to a depth of 100 metres, but its true madness and thrill lies in its ability to safely tumble, roll, swerve, vertically ascend and descend and generally zip around erratically under the sea. Its designers profess to the sensation being like piloting a fighter jet, and if that wasn't exciting enough, the controls can be easily switched between passengers, letting all aboard (there's a four-crew version too) take a turn at the wheel. As far as accessibility goes, this submersible also takes the crown. Rather than being only suitable for a super yacht, it can be easily towed behind a car and smaller marine craft.

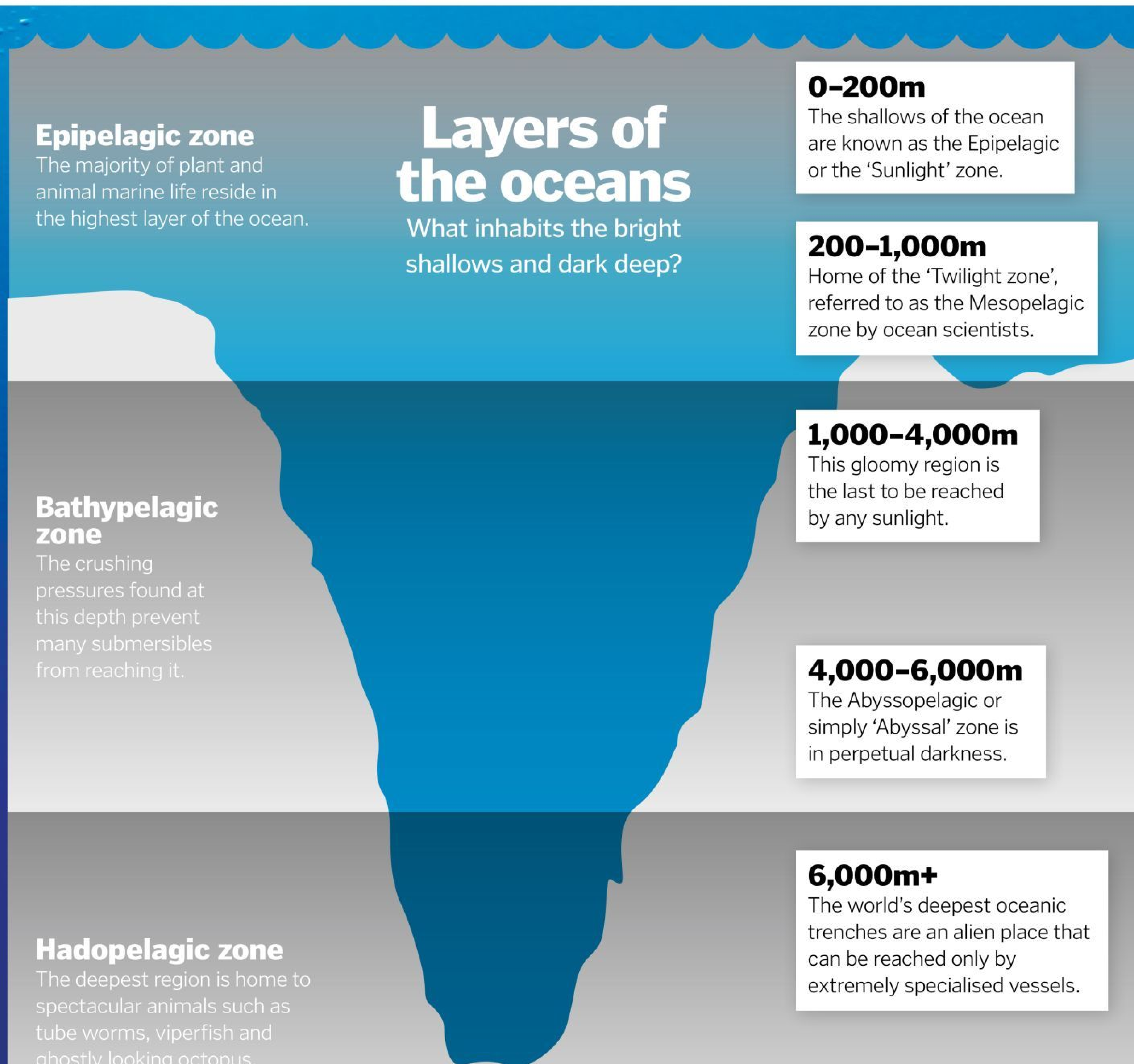
U-BOAT WORX HIPER SUB

DEPTH RATING: **100m**
MAX CREW: **2**
LIFE SUPPORT (HRS): **6**
MAX SPEED: **6kn**

The HiPer Sub series are purpose built to perform tricks under the water

Layers of the oceans

What inhabits the bright shallows and dark deep?



Epipelagic zone
The majority of plant and animal marine life reside in the highest layer of the ocean.

Bathypelagic zone
The crushing pressures found at this depth prevent many submersibles from reaching it.

Hadopelagic zone
The deepest region is home to spectacular animals such as tube worms, viperfish and ghostly looking octopus.

0–200m
The shallows of the ocean are known as the Epipelagic or the 'Sunlight' zone.

200–1,000m
Home of the 'Twilight zone', referred to as the Mesopelagic zone by ocean scientists.

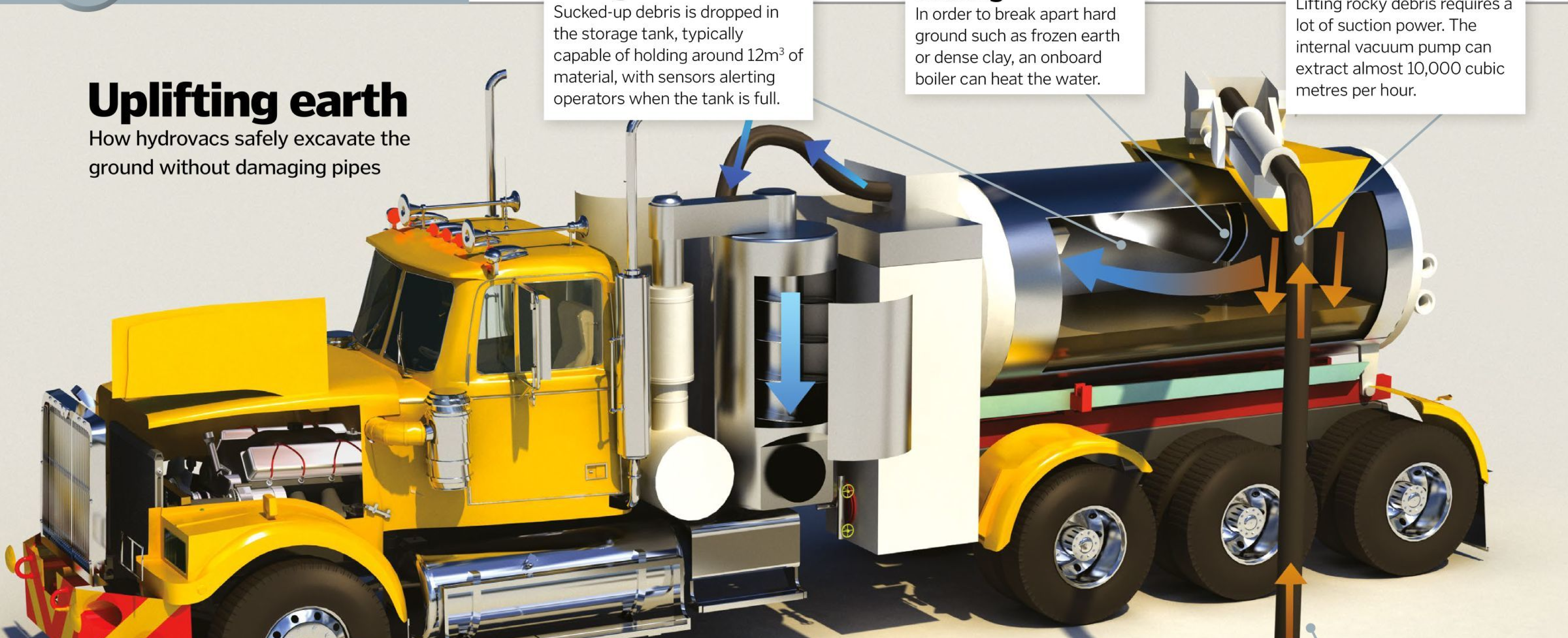
1,000–4,000m
This gloomy region is the last to be reached by any sunlight.

4,000–6,000m
The Abyssopelagic or simply 'Abyssal' zone is in perpetual darkness.

6,000m+
The world's deepest oceanic trenches are an alien place that can be reached only by extremely specialised vessels.

Uplifting earth

How hydrovacs safely excavate the ground without damaging pipes



Super-sucking excavator trucks

How do these hydro-vacuum vehicles suck up tons of rubble?

Long gone are the days of manual digging on construction sites with the introduction of these mammoth vacuum vehicles. Commonly known as hydrovac trucks, these purpose-built machines utilise hydro-vacuum excavation to break down the dense rock. There are two main components to achieve this: highly pressurised water is jetted onto the ground to break it apart and form a slurry. Simultaneously a vacuum boom sucks up the slurry and debris as it goes. The remains are stored in the truck's vast containment unit, until they're driven to a dumping site and removed from the bowels of the vehicle. Hydrovac trucks use different methods to expel the rocky remains, including a hydraulically lifted tank to tip out rubble and water, or a moving wall within the tank to push the ground out.

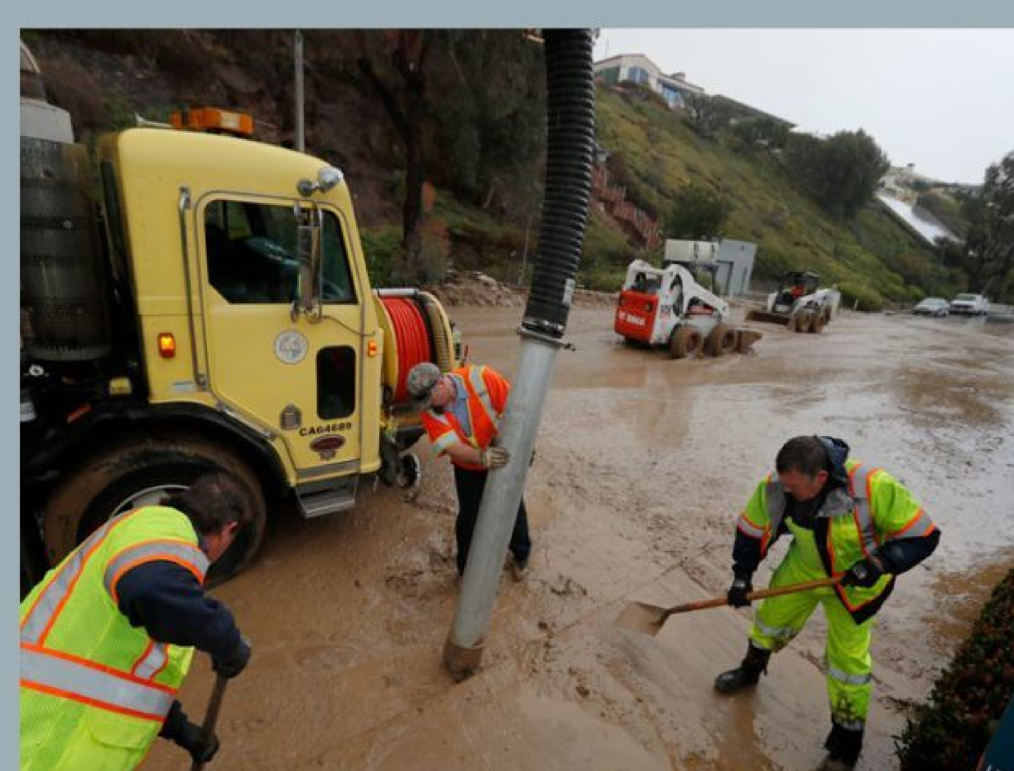
One of the biggest problems with digging underground is the potential for compromising water mains, communication lines, gas pipes or electrical cables. The hard tools used in manual digging are a particular threat to this underground infrastructure. However, as hydrovacs only use pressurised water to excavate, the risk of breaking a pipe or severing a cable is significantly reduced.

Hydrovacs are used to access underground infrastructure, including cleaning US storm drains

To the rescue

Although hydrovacs are used for everyday maintenance missions, they can also offer a helping hand in times of crisis, in particular landslides. These occur for several reasons, often when earthquakes or heavy rainfall loosens the ground – and the results can be extremely devastating.

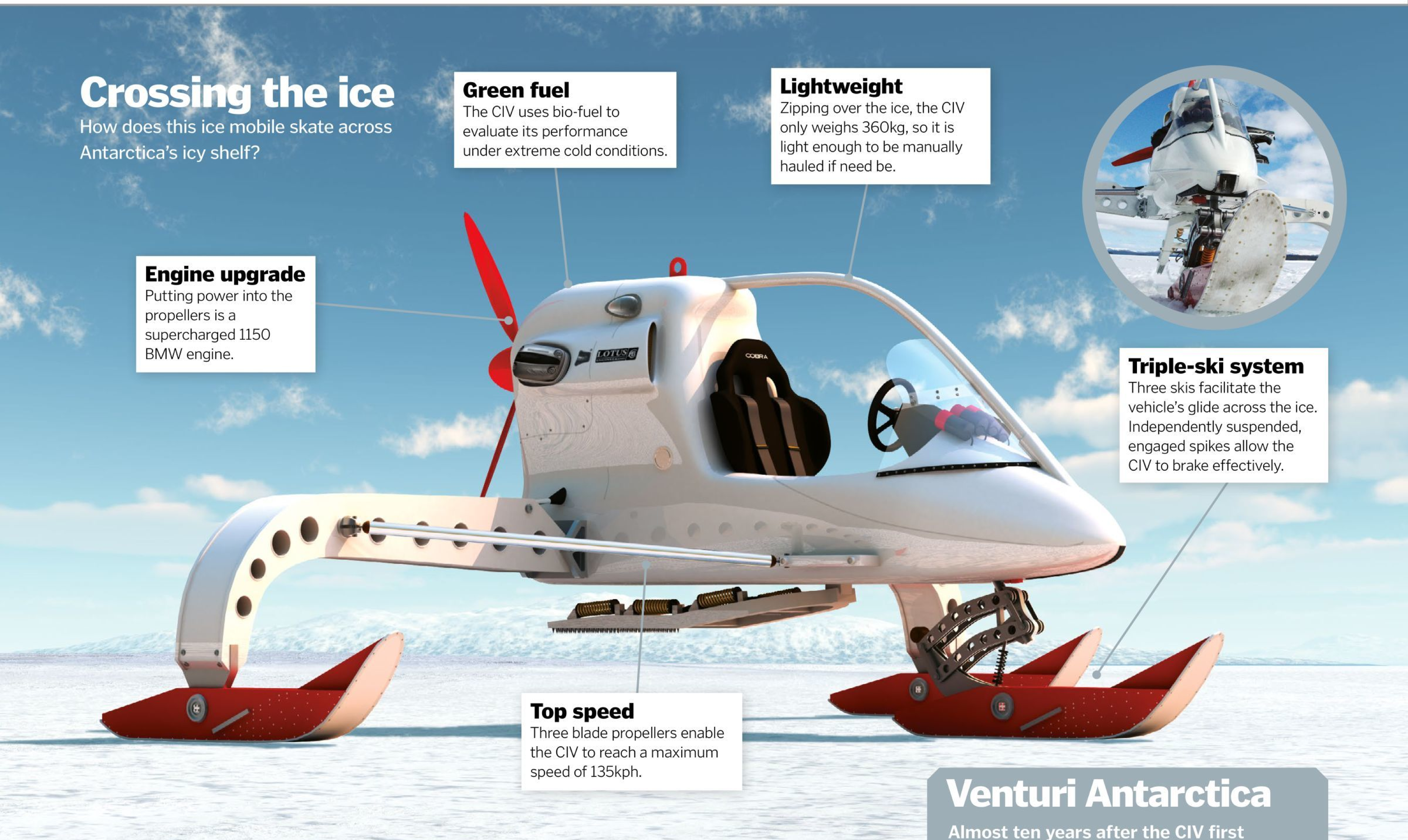
In early 2018 a landslide occured in California, depositing hundreds of tons of debris onto a highway. Hydrovac trucks, along with many other maintenance vehicles, arrived at the scene and used their vacuuming abilities to remove the mud and rubble, redistributing it to another site.



Hydrovacs helped clean up the debris from a landslide in California in 2018

Crossing the ice

How does this ice mobile skate across Antarctica's icy shelf?



Polar-exploring ice mobile

The bio-fuel-powered vehicle that can zip across Antarctica to reach the South Pole

In 2010 a team of researchers and engineers set out to achieve the first there-and-back vehicle crossing, nearly 4,000 kilometres, across Antarctica. Leading the assembly of research transport and a mobile laboratory was the first bio-fuelled machine to reach the South Pole: the Lotus Concept Ice Vehicle (CIV). It was also known as the Winston Wong Bio-Inspired Ice Vehicle in honour of the project's sponsor, Professor Winston Wong.

At its core, the functionality of the CIV is to aid the research conducted on the ice sheet. With built-in radar, the CIV's sensors can penetrate the ice and detect any surprises within it, such as crevasses, before the rest of the team encounter them. Mounted on three skis and thrust across the ice by way of three propellers, the CIV is able to navigate the unpredictable terrain of the Antarctic surface. One of the predominant reasons for the creation of the vehicle was to monitor and research the chilling effects of the environment on the CIV's bio-fuel reserves. As it's one of the regions of the planet most affected by pollution, green or zero-emission solutions for human activity at the Antarctic are paramount.

The Lotus Concept Ice Vehicle is 4.5 metres wide and 4.5 metres long

Venturi Antarctica

Almost ten years after the CIV first crossed Antarctica, a new generation of vehicles have been designed to withstand the continent's harsh conditions, most recently the Venturi Antarctica.

With the final model unveiled at the Prince's Palace in Monaco in late 2018, the two-ton vehicle is set to visit the ice shelf in 2019. The Venturi Antarctica is the first electrically powered exploration vehicle, equipped with an 80-horsepower motor system that can propel it at speeds of around 20 kilometres per hour. In order to combat the harsh conditions on the continent, the Venturi Antarctica travels on wheel-mounted caterpillar tracks and can withstand temperatures as low as minus 50 degree Celsius.

With a range of 45 kilometres, three passengers and luggage can zip to research areas previously difficult to access. The Antarctica completed a test run in Canada in February 2019.

Venturi's focus on Antarctica was inspired by Prince Albert II of Monaco's visit to the region

ROBOT

Words by **Scott Dutfield**

Drones have been designed to act as both surveillance and support aids for soldiers on the ground

WARS

THESE ARE THE MACHINES THAT WILL DOMINATE THE BATTLEFIELD ON THE FRONT LINES OF THE FUTURE

In November 2018, the UK's Ministry of Defence conducted the largest military robot exercise to date. Known as Exercise Autonomous Warrior, over 70 future technology examples were tested for their ability to support soldiers in conflict areas. More than 200 military personnel attended the event to test the suitability of these robots to join their ranks. From drone detectives to autonomous armed vehicles, How It Works travelled to a military base in Salisbury to discover which robots we might see on the front lines in the future.

Milrem Robotics have created an unmanned guided vehicle for autonomous resupply

The Marionette control system removes the need for human operators and converts existing tanks into remote-control robots

Military personnel can control Strike remotely to scope out battlefields

The TITAN Strike and Sentry work together to track targets and engage the enemy

REMOTE-CONTROL SOLDIERS

Human soldiers put their lives on the line in military conflict. However, collaboration between robotics engineers has resulted in the creation of mechanical soldiers to take some of the heat off their human comrades. A robot team known as TITAN Strike and Sentry, which has the potential to reach areas inaccessible to foot soldiers, has been created by Milrem Robotics and QinetiQ. Strike is armed with a machine gun and cameras, while Sentry acts a guide, using sensors and cameras to track targets before its partner goes in on the offensive. Both vehicles can be controlled remotely or via a preprogrammed route. The modular base unit housing the artillery is known as THeMis and can also be used as a resupply device due to its autonomous abilities. Sensor and mapping technology enable the robots to travel between base and battlefield delivering ammunition, medical and resource supplies.

Engineers have also created a way to hijack existing weaponry to create a new kind of robot. The British Warrior FV510 tank, which first entered service in 1988, has had a robotic overhaul with the Marionette universal system. Like a puppet on a string, this control system can be hardwired into the military tank, transporting control of the mammoth vehicles to soldiers several kilometres away.

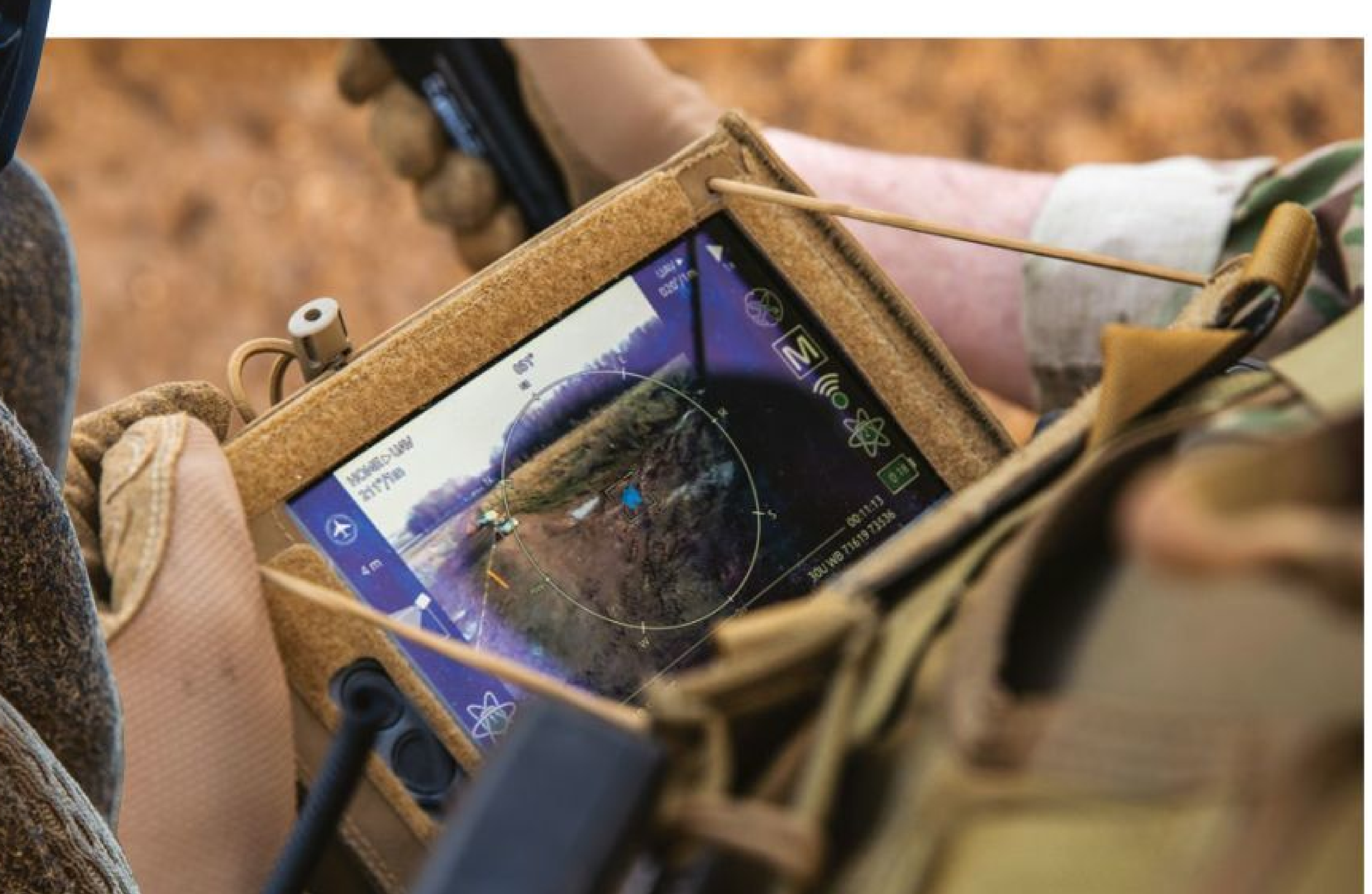
SPY IN THE SKY

Drones have become a revolution in many different industries, but now unmanned aerial vehicle (UAV) developers Threod Systems have created a heavy-duty one designed to act as an army's eyes in the sky, along with a delivery system for those on the ground. The KX-4 LE TITAN is a drone with a plug-and-play payload, thanks to a lift capacity of around six kilograms. Aerial mapping sensors, cameras and gimbals are some of the modular options that attach to it, allowing it to survey an area, track targets and lock-on up to five kilometres away. Also offering back-up from the skies, the TITAN can drop resources such as life jackets and even deliver stun grenades for combat support. Having eyes in the sky can offer unique tactical support, but if they're spotted, there are many ways to take them down, from frequency-emitting drone guns to actual bullet-loaded ballistics.

Stealth is key to staying airborne. Only 16.8 centimetres long, the Black Hornet PRS has been described as a form of nano surveillance for its ability to quietly zip ahead of the troops. Resembling a toy helicopter, this pocket-sized UAV is deceptively high-tech. It is equipped with advanced electro-optical and infrared cameras and sensors to offer the operators a clear view of the threats ahead.

"The TITAN can drop resources such as life jackets and even deliver stun grenades"

The Black Hornet PRS can fly 2km at speeds of up to 21.5kph


The Black Hornet PRS is almost silent, making it perfect for use in combat

The Throwbot 2 can clear obstacles up to 5cm tall

Robotic infiltrator

Designed to withstand repeated drops of 9.1 metres on concrete, the Throwbot 2 is a compact remote-controlled robot able to scope out potential threats without the need for human intervention. Equipped with a colour camera, microphone and infrared illumination, this tiny scout can survey indoor locations and feed information back to a handheld monitor to provide a better picture of what is inside. To maintain its stealthy nature, Throwbot is around 21 centimetres in length and emits less than 59 dBa from a one-metre distance (about the same as a radio turned down to low volume).

JACK OF ALL TRADES

THERE'S ONE MACHINE THAT CAN SEEMINGLY DO IT ALL – THE THEMIS IS ABLE TO CARRY OUT SEVERAL TASKS IN THE FIELD THANKS TO ITS MODULAR DESIGN

Launch pad
In collaboration with the KX-4 LE TITAN drone, this landing pad allows controllers to a select launch and landing sites in the field.

Scout
As robotic eyes on the ground, the THeMIS can be used as a simple patrol unit or observer.

Detective
Equipped with the Pegasus Multiscope, this module can survey areas difficult to reach by foot, and with built-in sensors it has the ability to monitor heat signatures and air particulates.

Bomb defuser
The THeMIS GroundEye has a module system that can detect explosive IEDs buried beneath the ground.

Weapon
As a robotic soldier, this weaponised module can lock on to targets and fire remotely.

Fire fighter
Swapping a gun for a hose, it can be used to direct water to the higher levels of a burning building.

Tankbuster
To disable enemy tanks, this THeMIS can be equipped with anti-tank missiles.

Medic
Supplies aren't the only thing this robot can transport. As a medevac module, the THeMIS can be used to load a stretcher carrying a wounded soldier, driving them away to safety.

Carrier
Fundamentally the THeMIS is a supply vehicle, enabling resources to reach soldiers at base or in the field without risking more lives during battle.

On board the HAWK

The dual-control training jet that helps the next generation of pilots prepare for combat

Words by **Scott Dutfield**

Getting into the cockpit of a jet engine aircraft for the first time is a daunting prospect for any trainee pilot. After spending years learning the theoretical physics and basics of flying, the Hawk is the next stage in their training and their first real venture into the skies in a working military jet.

The Hawk has played a key training role within the Royal Air Force (RAF) since the 1970s. Originally designed and constructed by Hawker Siddeley Aviation Limited (now known as BAE Systems) in 1971 and first flown in 1974, the Hawk promised a more agile way to fly. It replaced the Folland Gnat, a plane similar in weight and size. However, the Gnat's cockpit only offered a single seat, leaving inexperienced pilots to fly solo. The Gnat saw the end of its training career in 1979 when the new, purpose-built Hawk T1 swooped in to take over.

What makes the Hawk unique for training the next generation of RAF pilots are its dual-control capabilities. Similar to the dual-control cars used by driving instructors, the two-man tandem cockpit enables a teaching pilot to sit behind their student and intervene when needed. For teaching the basics, the jet's cockpit is relatively unchanged since the plane's introduction to the Air Force. Pilots rely on dials, gauges and the view through the glass roof to navigate and fly the plane. However, BAE Systems has integrated multi-functional digital displays in the newer model, the Hawk T2.

Offering an introduction to fast jets, the Hawk is designed to reach Mach 0.88 during flight and Mach 1.15 during a dive. The Mach number relates to the jet's speed when compared to that of sound (equal to Mach 1), so the Hawk can manoeuvre at speeds known as transonic, paving the way for pilot training on supersonic jets such as the F-35 Lightning II.

Although predominantly used as training jet, the Hawk has proven itself as a combat aircraft and has also been used for reconnaissance and surveillance. Currently, around 1,000 aircraft have been sold to 18 countries across the globe.

Aerial acrobats

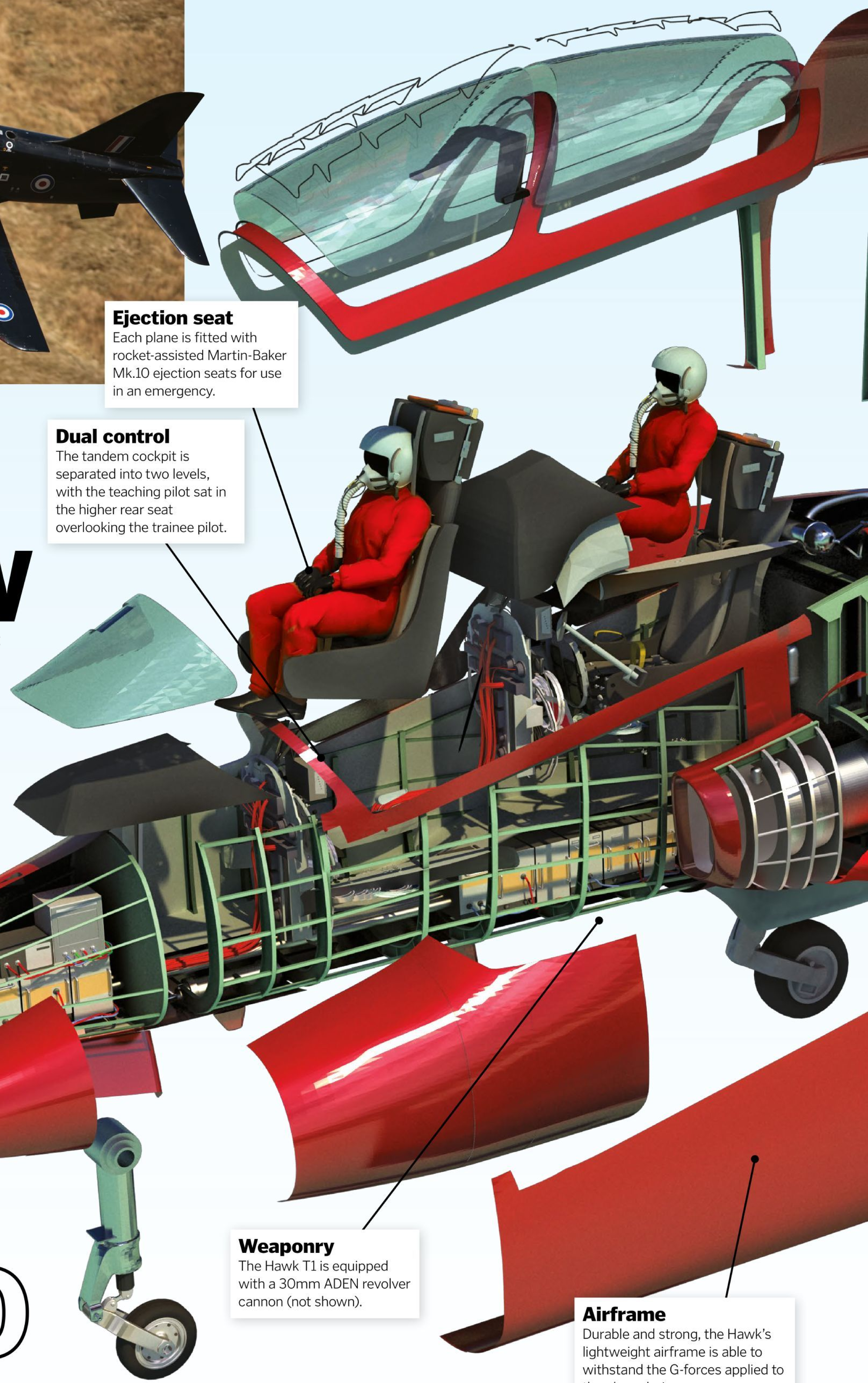
Though they triumph as a training jet, the Hawk is most recognised as the type of plane seen flying in formation during a Red Arrows display. Originally sporting a black coat of paint, the newly introduced Hawk T1 had a red makeover upon joining the ranks of the Royal Air Force Aerobatic Team in 1979. Debuting synchronised sky routines a year later, the Hawk T1 proved its ability to perform stunning displays.

These gravity-defying stunts, however, can be limited by the weather. In order to carry out the iconic loops, the cloud base needs to be above 1,700 metres so the aircraft avoid entering it and disappearing from sight. If the clouds are lower than that, they're limited to rolling displays, flypasts and steep turns.


An RAF Hawk T1 training aircraft, which has been painted black to make it easily visible and reduce accidents

Inside a RED ARROW

What enables the Hawk T1 to take flight and perform a Red Arrows routine?

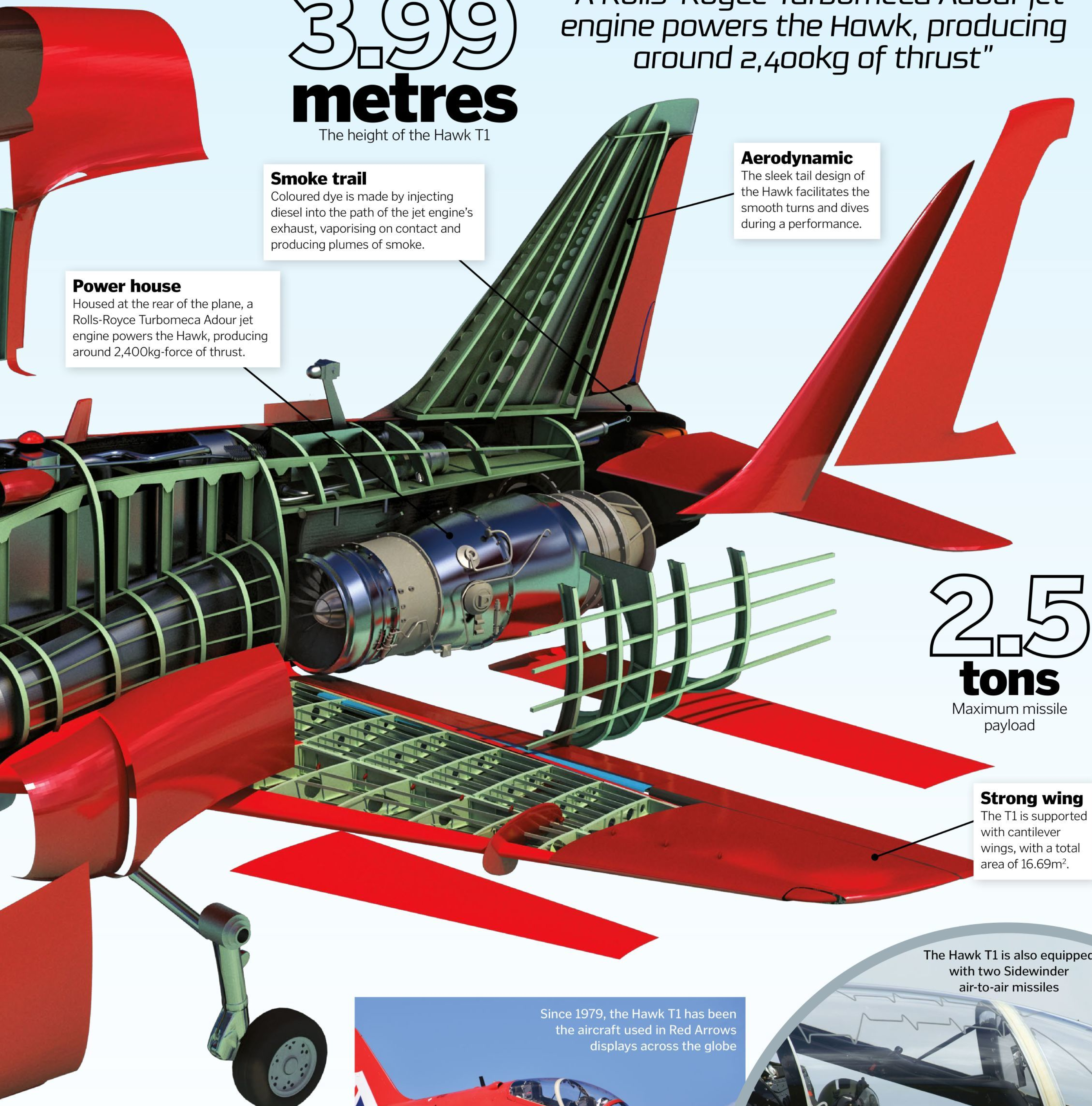


11.96 metres
The fuselage length of the Hawk T1

3.6 tons
The total weight of the Hawk T1

1,000 kph
The Hawk T1's maximum speed

"A Rolls-Royce Turbomeca Adour jet engine powers the Hawk, producing around 2,400kg of thrust"



3.99 metres
The height of the Hawk T1

Smoke trail
Coloured dye is made by injecting diesel into the path of the jet engine's exhaust, vaporising on contact and producing plumes of smoke.

Aerodynamic
The sleek tail design of the Hawk facilitates the smooth turns and dives during a performance.

Power house
Housed at the rear of the plane, a Rolls-Royce Turbomeca Adour jet engine powers the Hawk, producing around 2,400kg-force of thrust.

2.5 tons
Maximum missile payload

Strong wing
The T1 is supported with cantilever wings, with a total area of 16.69m².

9.39 metres
The wingspan of the Hawk T1

Since 1979, the Hawk T1 has been the aircraft used in Red Arrows displays across the globe

The Hawk T1 is also equipped with two Sidewinder air-to-air missiles

How cement-mixing vehicles work

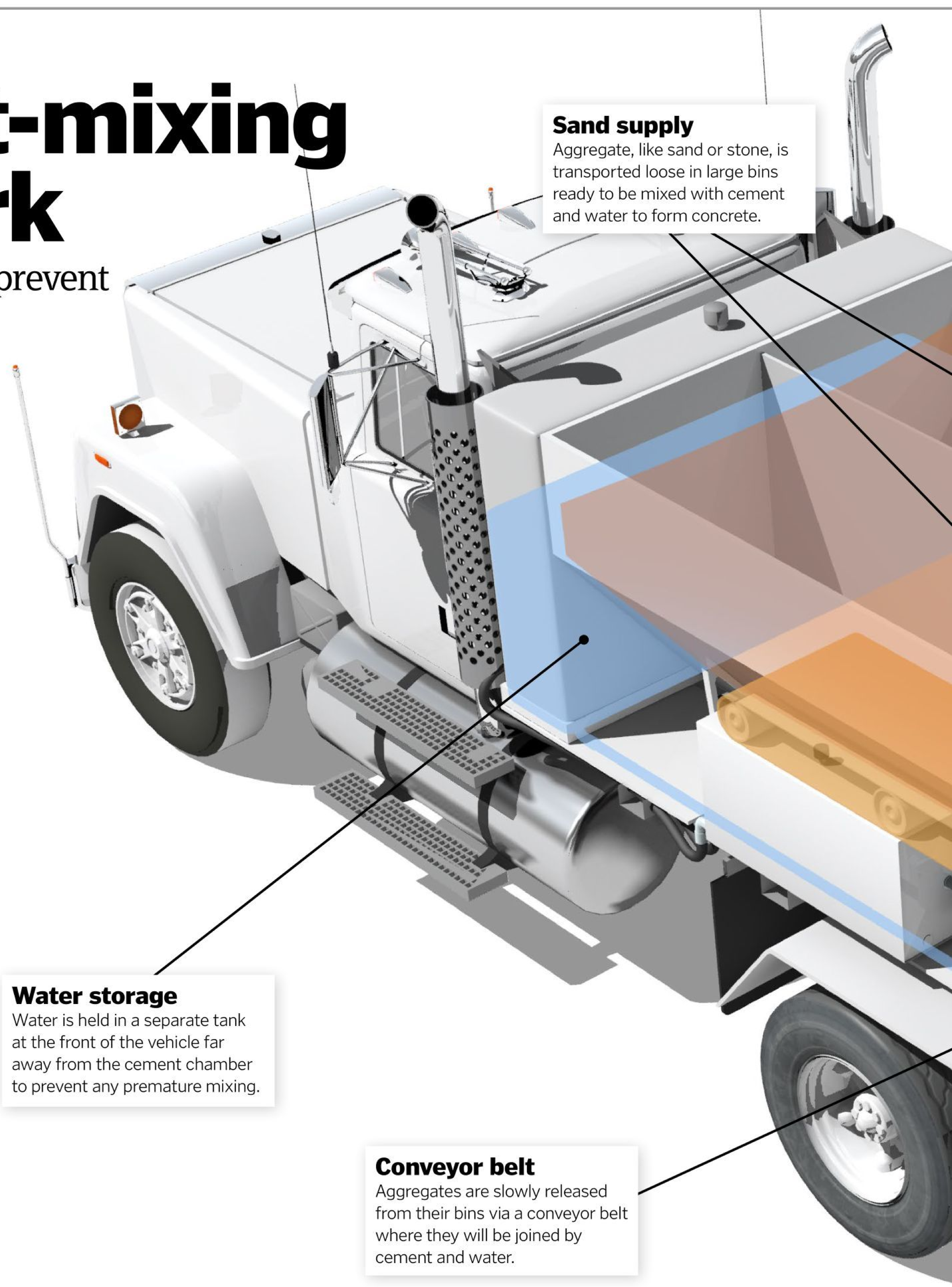
How do these concrete transporters prevent their load from turning rock solid?

Concrete mixer trucks, delivering vital raw material, bear the weight of around 13,500 kilograms of cement. These vehicles have the repetitive task of continually cycling its contents. A cocktail of aggregate (sand or stones), cement and water are hurled into the drum-shaped rotating barrel at a concrete-production plant. Interior fins, shaped and arranged like a screw, fold the ingredients together. During its journey from the production plant to construction project, the drum is constantly turned by an external motor.

Once it reaches its final destination, hydraulics lift the drum and its cement concoction, allowing gravity to pull the freshly formed concrete down a delivery spout. The mixing fins also lend a helping hand, spinning in the opposite direction to that of the mixer, to force the material out of the drum.

This method of concrete creation comes with a race against the clock. Known as 'batch mixing', this traditional way of transporting a pre-made product comes with a quick expiry time: There is a short window of opportunity to distribute the solidifying substance before it sets and hardens, typically around 90 minutes. This constraint is one of the reasons manufacturers have created a portable concrete factory in the form of volumetric cement mixer trucks.

These building behemoths carry uncombined ingredients to a construction site and form fresh concrete at the touch of a button. Using a built-in micro production line, the main ingredients are fed to a mixing auger (rotating screw) via conveyor belts and pipes. The result is fresh, made-to-order, fluid concrete, ready to be laid.



Sand supply
Aggregate, like sand or stone, is transported loose in large bins ready to be mixed with cement and water to form concrete.

Water storage
Water is held in a separate tank at the front of the vehicle far away from the cement chamber to prevent any premature mixing.

Conveyor belt
Aggregates are slowly released from their bins via a conveyor belt where they will be joined by cement and water.

Mobile concrete factory

How do volumetric mixer trucks turn sand and cement into fresh concrete?

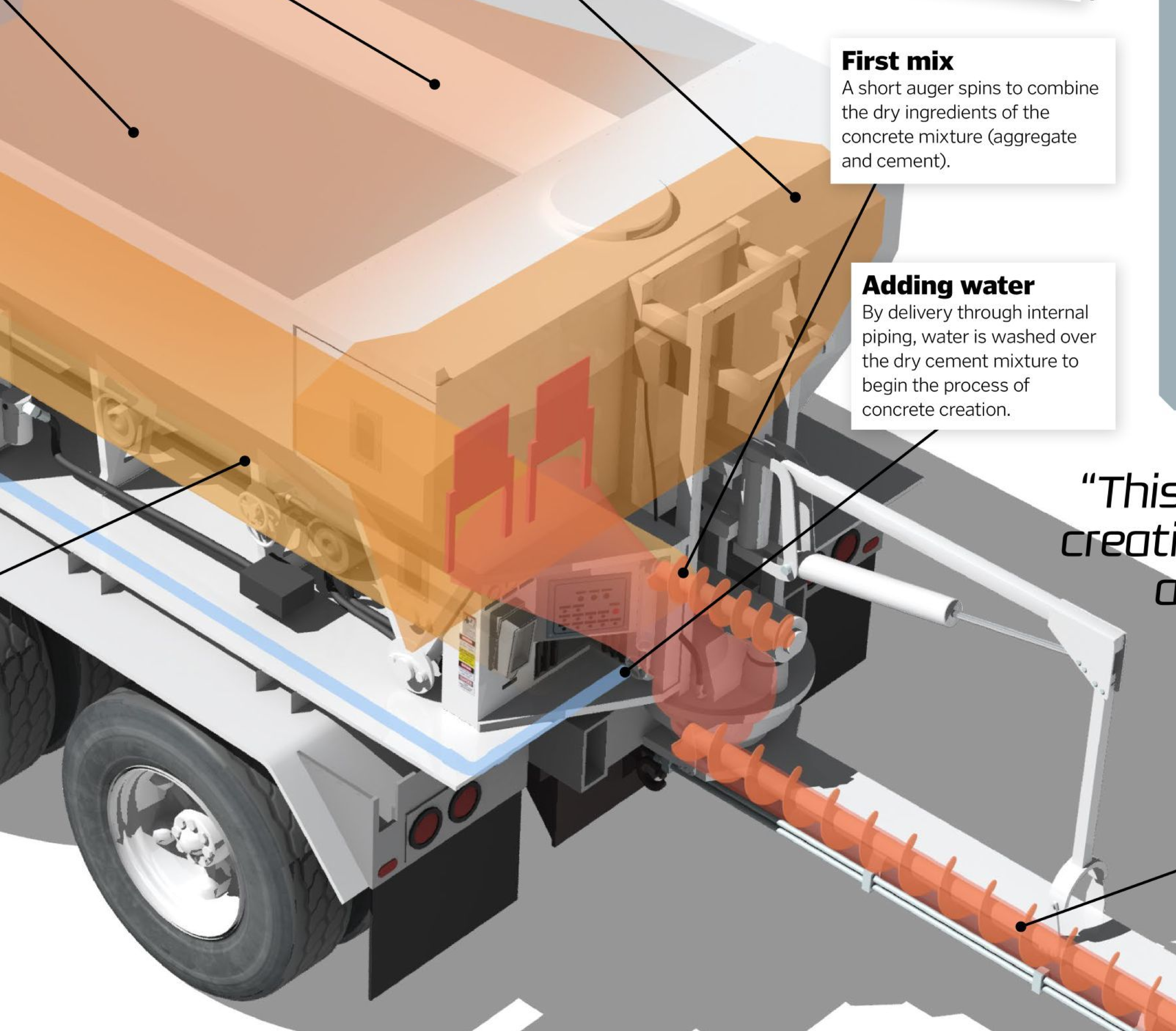
Essential to the construction industry, concrete-mixer trucks continually spin their contents to prevent it setting in transit

Paving the way

The principle mechanics of the humble drum-shaped concrete mixer has remained relatively unchanged since its creation around 100 years ago. Taking cement mixing from horse-powered to horsepower, the first motorised concrete mixers sprung into action in the early 1900s. The first patent application for a vehicle-driven mixer is believed to have been filed by American inventor Stephen Stepanian back in 1916 and although the design is reminiscent of today's vehicles, the patent was denied. Later creations came from inventors such as Ackert Bickel, who successfully patented the first concrete-mixer truck in 1920. Following the same principles of modern-day machines, Bickel's mixer was also designed to transport premade mixtures onto a site.

Aggregates, such as sand or gravel, and water are used to form concrete

©Getty



Cement mix
Essential to concrete creation, cement is made from grinding down rock, such as limestone, shells and chalk.

First mix
A short auger spins to combine the dry ingredients of the concrete mixture (aggregate and cement).

Adding water
By delivery through internal piping, water is washed over the dry cement mixture to begin the process of concrete creation.

Mix well
The main auger mixes all concrete ingredients, repeatedly turning to completely combine them.

Ready-made concrete
Fresh off the conveyor belt, viscous concrete flows out of the delivery spout to pour directly on-site.

©Illustration by Adrian Mann

Pumping power

To deliver concrete to those hard to reach places, such as at the top of a building, mobile mixers call upon the help of another vehicle known as a concrete pump truck. Acting as an extension cable for concrete, these vehicles often come with an extendable robotic arm or boom to maximise the distance it can be poured. Working in unison, the drum-shaped mixer ejects its concrete cargo into the metal grate at the rear of the pump truck. A hydraulic pump system then forces the fluid material through a large pipe running along the boom arm and out through a delivery hose, which is close to the ground.

©Alamy

Concrete mixers and pumps work together to distribute the concrete around a construction site

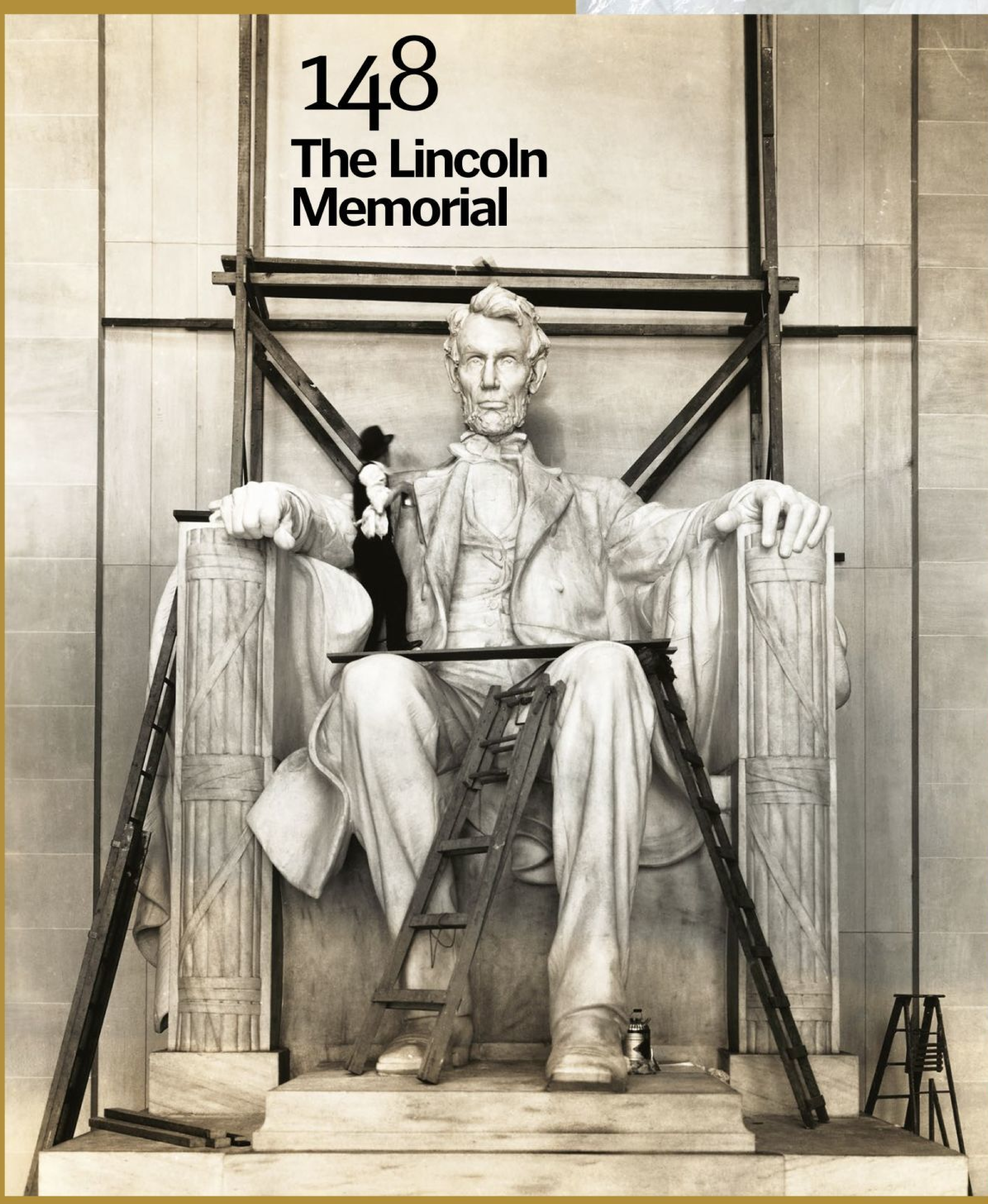
"This method of concrete creation comes with a race against the clock"

©Alamy

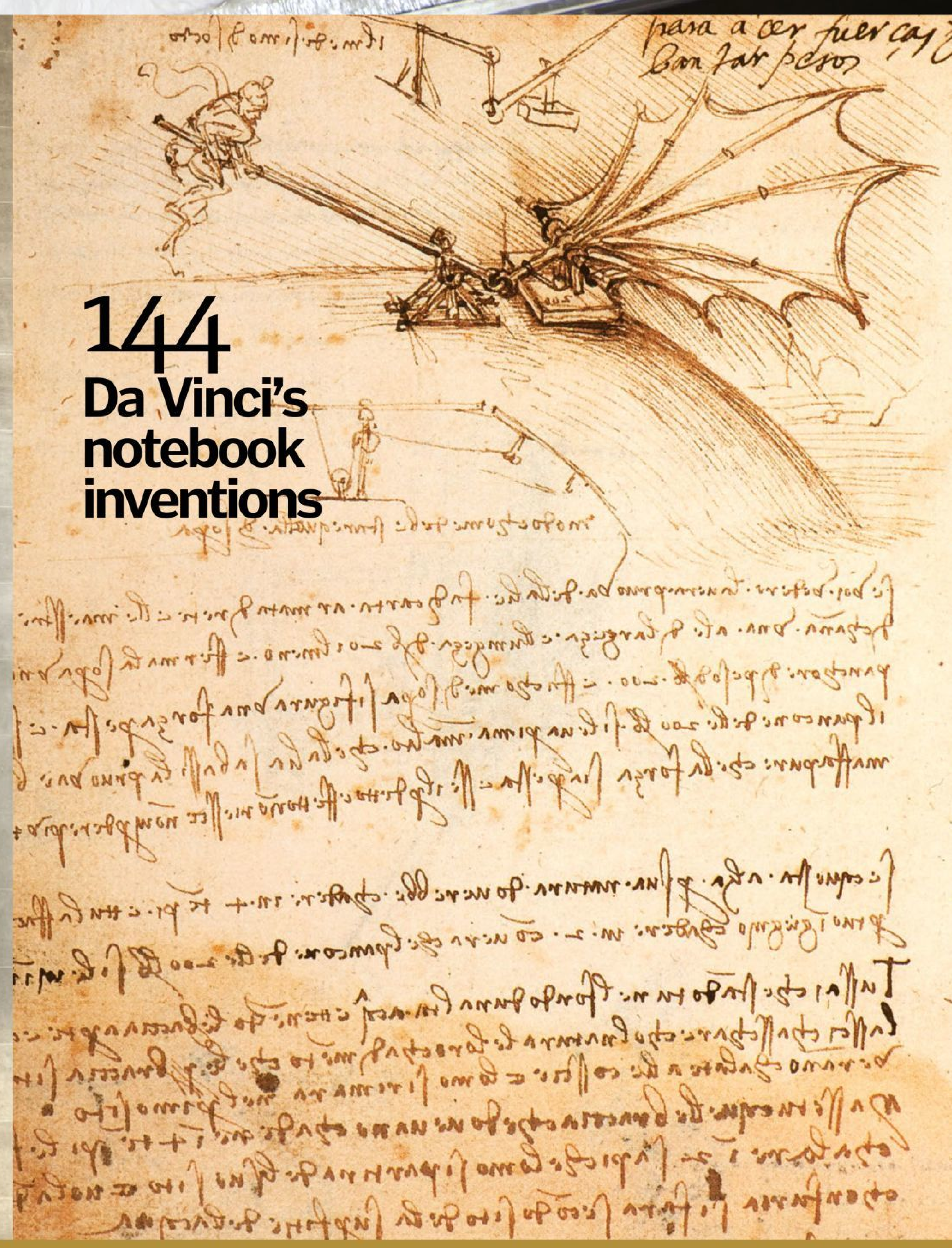
Volumetric concrete mixers are growing in popularity for their ability to make large amounts of concrete on a building site

HISTORY

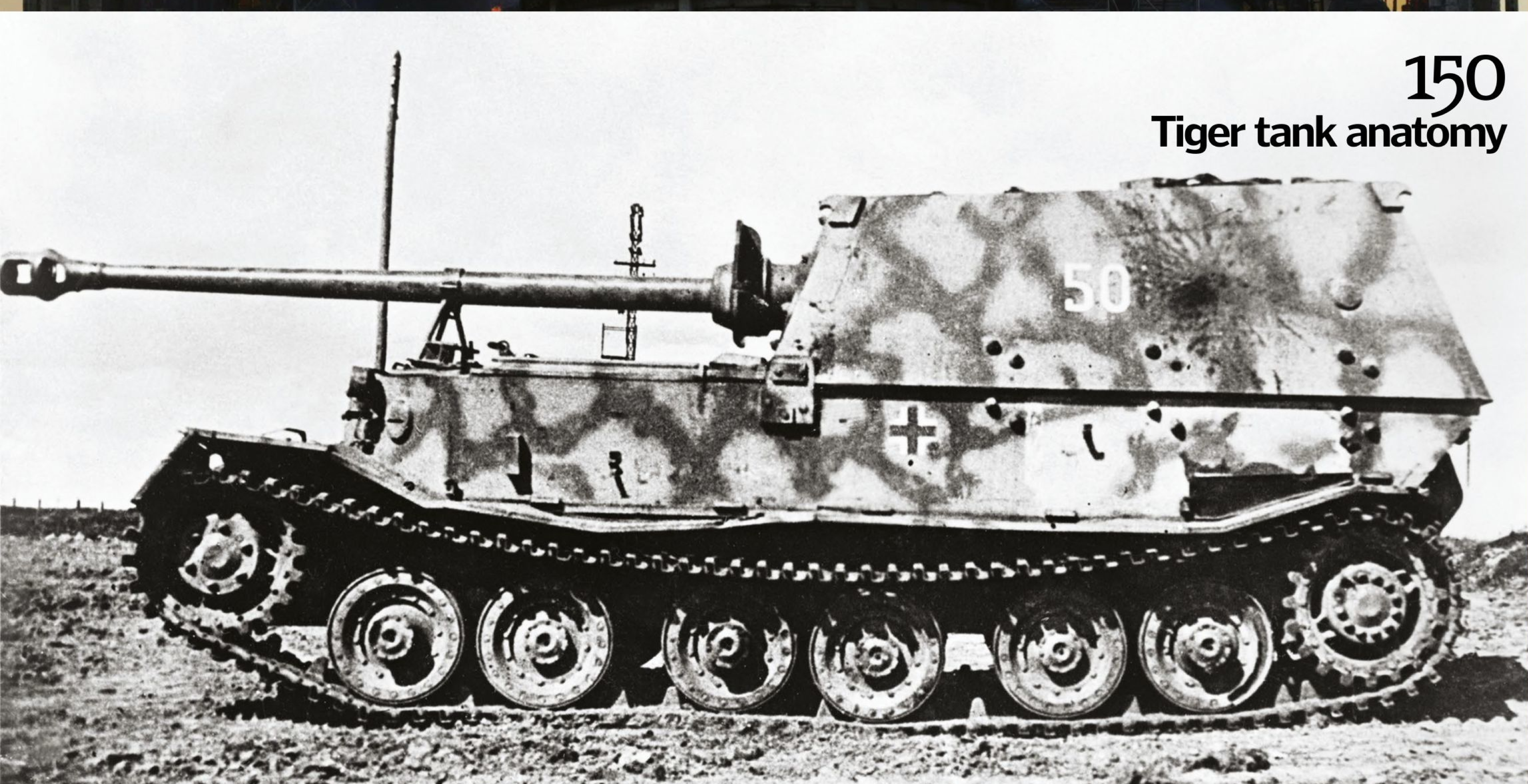
136 **Frozen in time**



148 **The Lincoln Memorial**



144 **Da Vinci's notebook inventions**



FRO

IN

The incredible ways nature has preserved prehistoric humans and beasts for us to find today

Words by **Amy Grisdale**

TIME

ZEN

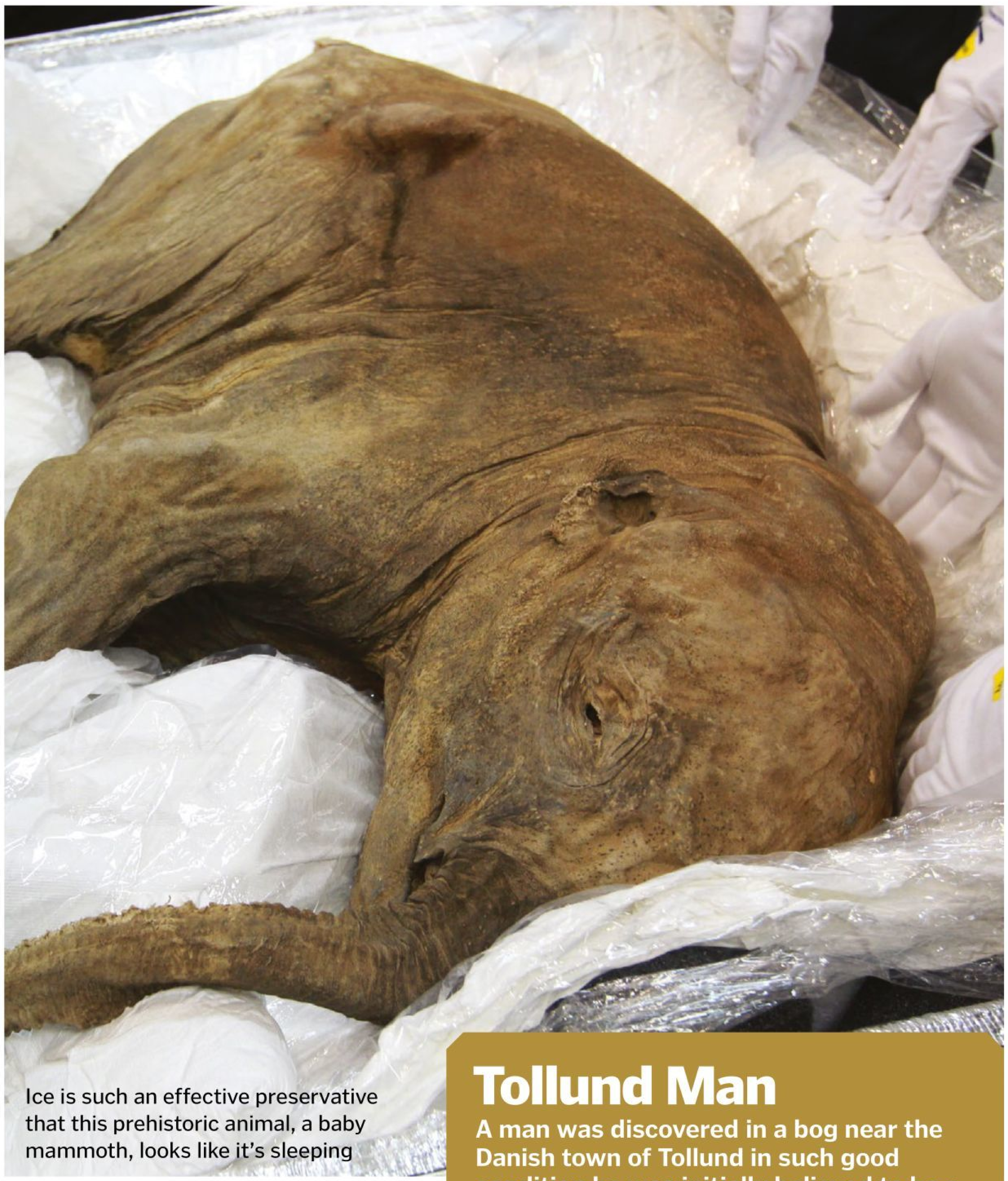
Borremose Man
This body, dating from around 840 BCE, was found preserved in a peat bog in Denmark in 1946

The Earth has experienced monumental changes since it was formed some 4.5 billion years ago. It has undergone alternating phases of cooling and warming, and this swinging between extremes of temperature dramatically changed the ecosystem. It brought about mass extinctions and the chance for new species to evolve in their place. The animals that ceased to exist left impressions, from partial footprints to intact fossilised skeletons. In some circumstances, however, animals of the past found their way into environments that preserved their entire bodies while the rest of the species rotted away.

One excellent method of animal preservation is freezing. Cold weather grinds the speed of organic decomposition to a halt by preventing the growth of bacteria that would otherwise feed on the decaying flesh. Temperatures were five to 22 degrees Celsius colder than today's climate in the most recent ice age. Animals were well insulated with thick hair, such as the great woolly mammoth, or took shelter from the cold

Carcasses trapped in tar pits attracted carnivores, who also got stuck in the sticky substance

Tusk hunters are always on the trail of precious prehistoric ivory



Ice is such an effective preservative that this prehistoric animal, a baby mammoth, looks like it's sleeping

like cave lions. Now most of the world has defrosted, but there are still areas that remain frozen, such as parts of Russia and Asia. Animals that lived and died in this bygone era have since been plucked from permafrost (a permanently frozen layer in the ground) with their bodies intact. A steppe bison that lived 36,000 years ago was uncovered in pristine condition in 1979. Its rear end still bore the claw and tooth marks from the Ice Age lion that killed it.

Specimens that have survived thousands of years often became trapped somehow before a sudden plummet in temperature. The presence of food in the stomachs of Ice Age animals indicates that their bodies were frozen rapidly, preventing decay.

A large proportion of frozen remains are unearthed by miners on the hunt for precious metals. Scientists are invited to remove and study the remains. They are then able to draw conclusions about how the animal lived day to day and what may have led to its extinction. Scrutiny of a woolly rhino found by gold miners in northern Russia in 2007 convinced researchers that the species died out because its legs were too short to move efficiently through deep snow.

"Lack of oxygen, low temperature and acidic water worked together to 'pickle' animal remains"

In the absence of ice, nature has other ways to preserve body tissue. An extremely important factor in preventing decomposition is separation from oxygen. Europe's peat bogs have a magical combination of a lack of oxygen, low temperature and acidic water, which works to 'pickle' the remains of any animal that meets its end in the mud. Over time, layers of moss form on the bog's surface and release chemicals that halt bacterial growth.

Some of the most famous remnants of the past uncovered in these bogs are almost immaculately preserved human remains, along with a plethora of bizarre ancient artefacts that have been recovered in recent years. Huge hunks of an edible waxy substance are sometimes found with these 'peat-bog men' that are thought to be made of dairy or meat. This

Tollund Man

A man was discovered in a bog near the Danish town of Tollund in such good condition he was initially believed to be a recent murder victim. The body had been lying in rest for some 2,300 years, still dressed in primitive clothing. He appeared to indeed have been murdered, but the culprits themselves were long dead. Peat bogs may have been ancient grounds of burial or even ritual sacrifice.

'Tollund Man' was found with a braided leather cord wrapped tightly around his neck, and it's unclear whether he was hanged or strangled. The absence of trees across stretches of bog may have made people feel a connection to the heavens and therefore made it a place of religious significance.

Tollund Man is so well preserved even his last facial expression is clear

Bog embalming

Chemicals in Europe's bog waters are a perfect mix for preservation

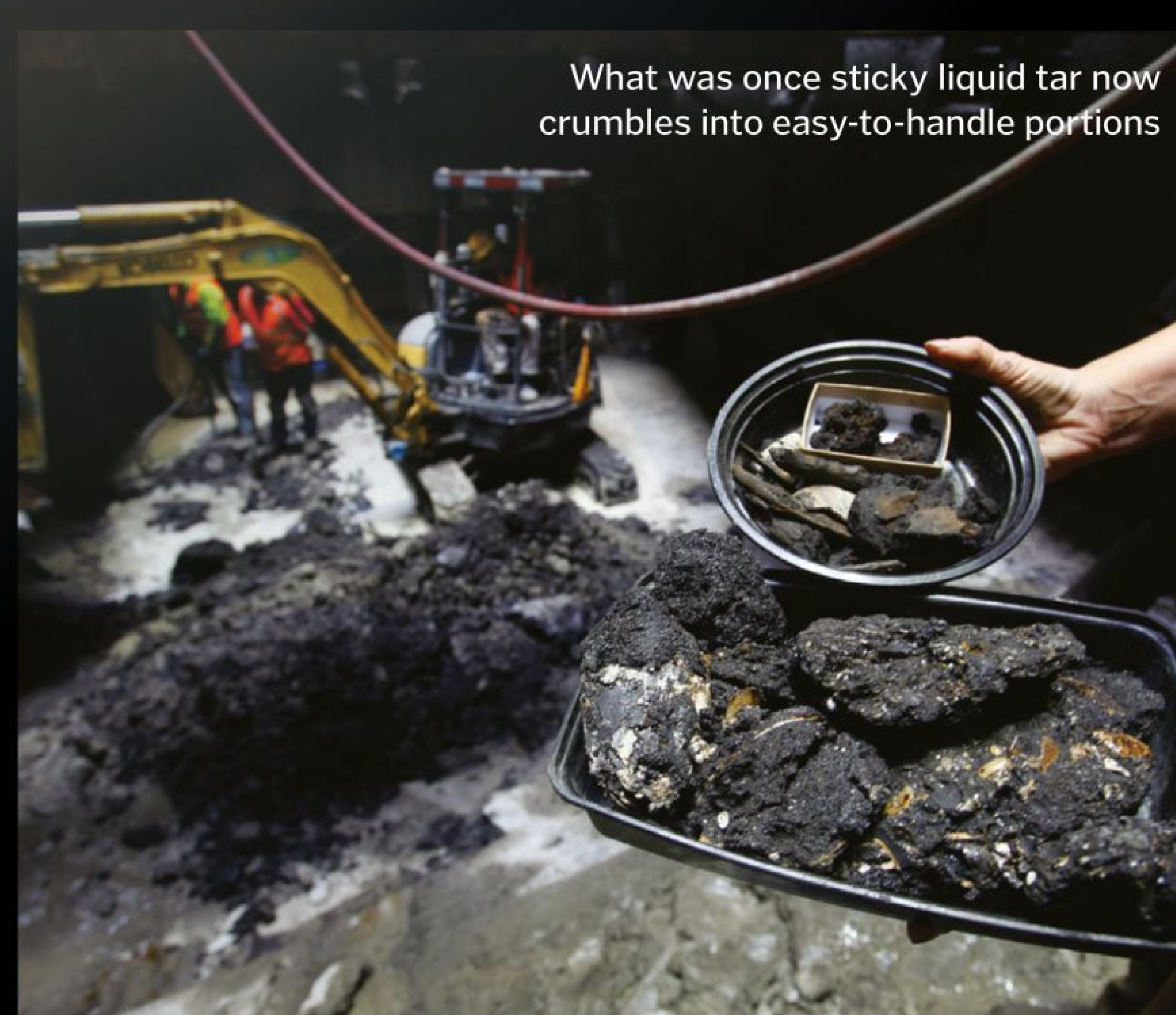
Raised bed
Elevated bogs contain the least oxygen but the most acid. These are the best at keeping a body fresh.

No air
At depths of 30-50cm there is no oxygen left in the acidic soil. Bacteria cannot break the body down.

Sphagnan
Decaying moss releases a carbohydrate called sphagnan. This polymer extracts calcium from the bones, leaving the body soft and squishy.

Under pressure
The weight of the water forces the peak soil to pack together tightly and nestle closely around the person.

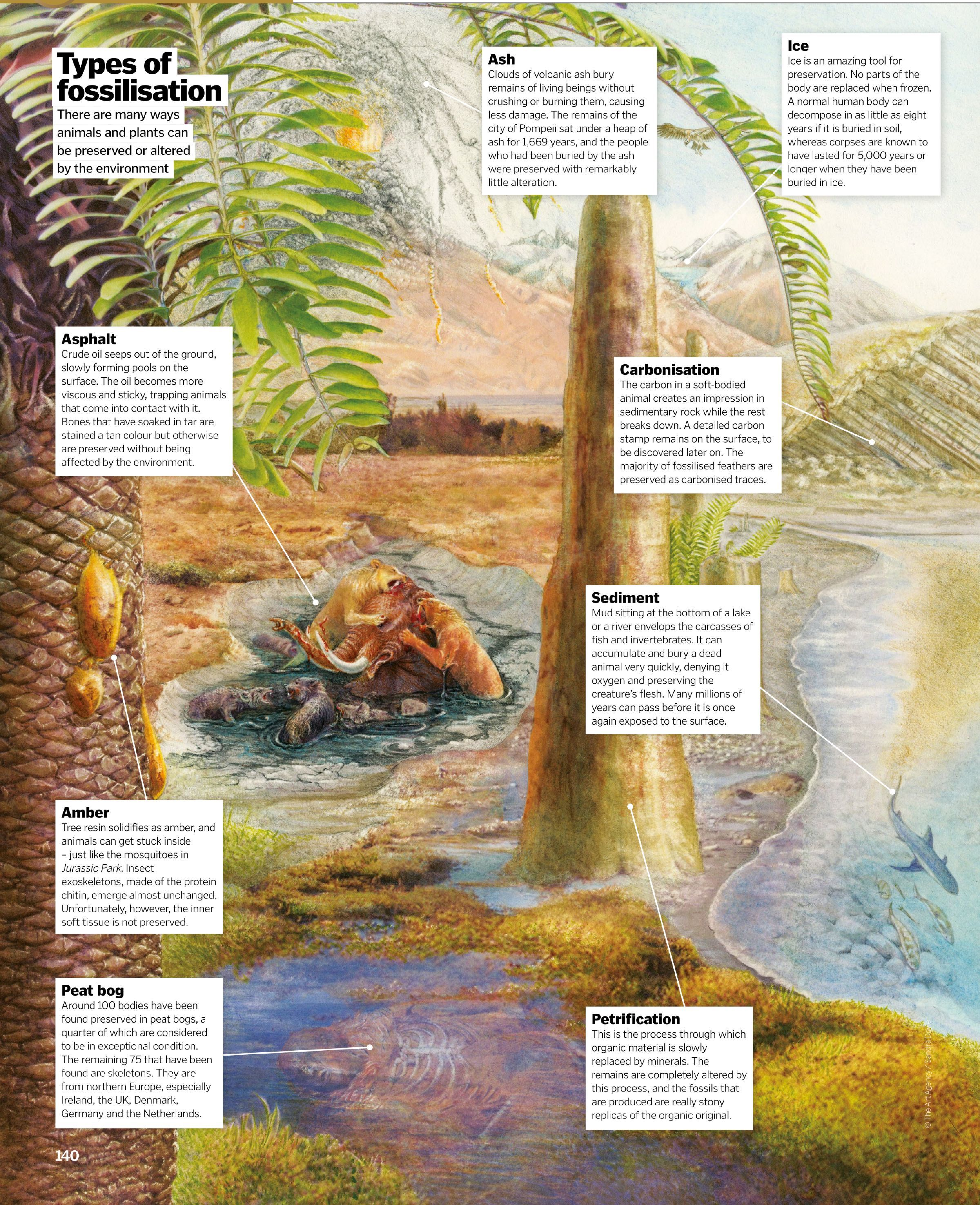
The Tollund Man was killed with this leather rope, and his hat is made of skin



What was once sticky liquid tar now crumbles into easy-to-handle portions

Types of fossilisation

There are many ways animals and plants can be preserved or altered by the environment



Ash
Clouds of volcanic ash bury remains of living beings without crushing or burning them, causing less damage. The remains of the city of Pompeii sat under a heap of ash for 1,669 years, and the people who had been buried by the ash were preserved with remarkably little alteration.

Ice
Ice is an amazing tool for preservation. No parts of the body are replaced when frozen. A normal human body can decompose in as little as eight years if it is buried in soil, whereas corpses are known to have lasted for 5,000 years or longer when they have been buried in ice.

Asphalt
Crude oil seeps out of the ground, slowly forming pools on the surface. The oil becomes more viscous and sticky, trapping animals that come into contact with it. Bones that have soaked in tar are stained a tan colour but otherwise are preserved without being affected by the environment.

Carbonisation
The carbon in a soft-bodied animal creates an impression in sedimentary rock while the rest breaks down. A detailed carbon stamp remains on the surface, to be discovered later on. The majority of fossilised feathers are preserved as carbonised traces.

Sediment
Mud sitting at the bottom of a lake or a river envelops the carcasses of fish and invertebrates. It can accumulate and bury a dead animal very quickly, denying it oxygen and preserving the creature's flesh. Many millions of years can pass before it is once again exposed to the surface.

Amber
Tree resin solidifies as amber, and animals can get stuck inside – just like the mosquitoes in *Jurassic Park*. Insect exoskeletons, made of the protein chitin, emerge almost unchanged. Unfortunately, however, the inner soft tissue is not preserved.

Peat bog
Around 100 bodies have been found preserved in peat bogs, a quarter of which are considered to be in exceptional condition. The remaining 75 that have been found are skeletons. They are from northern Europe, especially Ireland, the UK, Denmark, Germany and the Netherlands.

Petrification
This is the process through which organic material is slowly replaced by minerals. The remains are completely altered by this process, and the fossils that are produced are really stony replicas of the organic original.

DID YOU KNOW? *Frozen extinct animals may have enough good-quality DNA for cloning if a suitable surrogate can be found*

'bog butter' may well have been a treasured food product to slather on Bronze Age bread. It's possible that people of the past stored their butter in bogs to keep it cool and fresh, long before the days of refrigeration. It worked so well that this ancient spread is thought to still be edible – so long as the diner can ignore the smell.

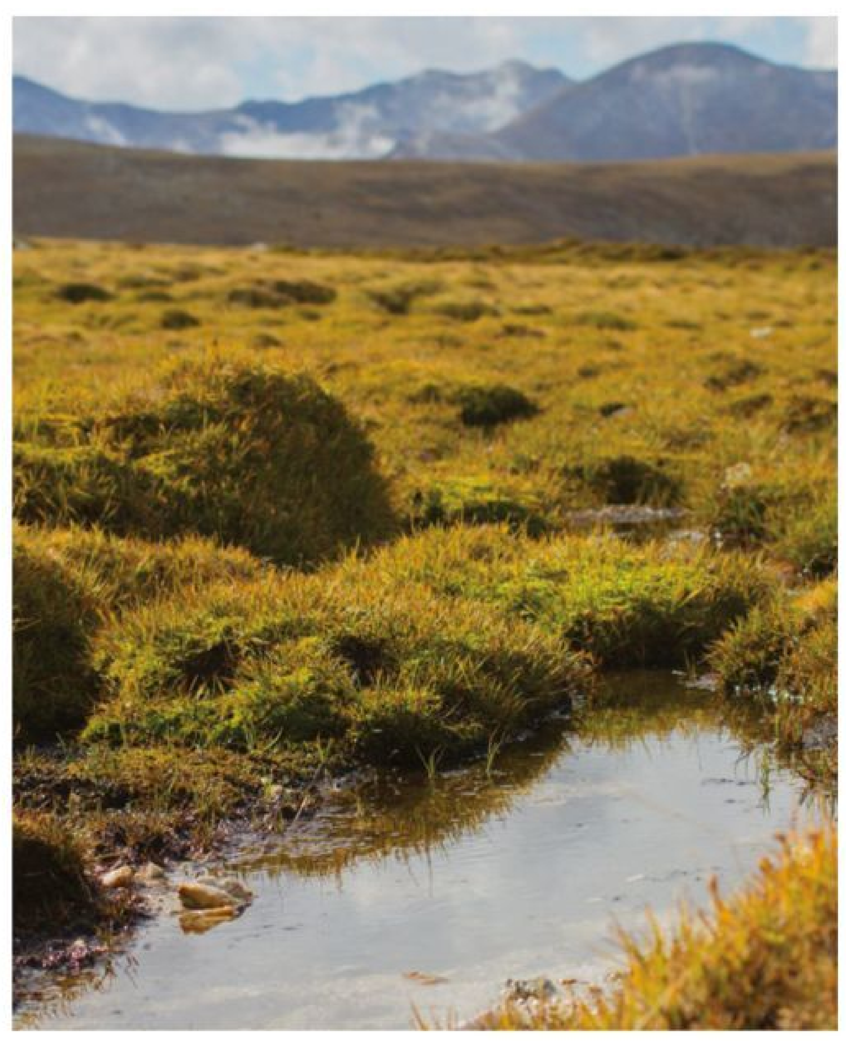
Animals can get locked in a kind of time capsule by getting stuck in tar pits. In some parts of the world, springs of natural asphalt can seep up to the ground as thick crude oil. It accumulates and eventually forms a pool, the surface of which reacts with air to become thicker and stickier. We call these tar pits, and each one is a snapshot back in time. Prehistoric animals would get trapped and struggle to free themselves. The resulting commotion would then attract predators, some of which would be lost in the tar themselves. Thousands of years later, the solidified tar began to be mined as asphalt, and the treasures within came to light.

> "Prehistoric animals would get stuck in the tar and struggle to free themselves"

La Brea is a world-renowned tar pit in Los Angeles, California. It trapped creatures for over 30,000 years, and new discoveries are still being made to this day. The site has been under excavation since 1913, and over 3.5 million specimens have been been found so far. More than 600 species of animals and plants have been identified from these remains, but most discoveries were bones of large animals. 90 per cent were carnivores like American lions and dire wolves. 4,000 dire wolves have been retrieved from the tar, and some 400 of their skulls are on display at the George C. Page Museum that stands on the excavation site.

Humans have learned so much from these pockets of prehistory. We have pieced together the events of evolution and have a detailed understanding of how we reached today. Chunks are missing, but areas that have preserved the past are helping us fill in the blanks.

The La Brea tar pit contains thousands of examples of preserved prehistoric creatures



Peat bogs, unremarkable at first glance, contain incredible pieces of history

How tar preserves prehistoric animals

Low-grade crude oil seeps out of the ground, encountering air for the very first time. Contact with oxygen causes small and simple hydrocarbon chains to degrade or evaporate. As the lighter fractions of oil disappear, the remainder becomes purer and is less likely to escape. The tar begins to harden when it touches the cool air but remains viscous enough for a heavy animal to sink in.

Dust, leaves or even water can camouflage the tar's surface, making it easy for a wandering mastodon (a kind of prehistoric elephant) to stray into a natural vat of tar. It calls out to other members of its species for help, inadvertently alerting wolves and big cats to its plight. Even if it dies of starvation or dehydration, it takes up to 20 weeks to sink. During this time, it is visited by hungry predators that are then at risk of getting stuck themselves.

The George C. Page Museum opened in 1977, and an excavation is underway that has the potential to double its collection

Five incredible ice mummies

These frozen prehistoric animals are superbly well preserved and now famous around the world

Sasha

This woolly rhino baby was the first young member of its species ever found. It's unclear if it is male or female, but the horn size suggests it had been weaned by the time it died. It roamed the mammoth steppe, a dry, cold region from Spain to Siberia.

Lion or lynx

A squashed, mummified cat was unearthed in eastern Siberia in 2017. It could either be a lynx kitten or a cave lion cub. Its coat is in beautiful condition, but we can't be sure of the species as we simply don't know what a cave lion truly looked like.

Death by drowning

Mammoths from 40,000 years ago have been studied via CT scans. The results showed that two calves, recovered from different regions of Siberia, had both choked on mud. They otherwise appeared plump and healthy.

Old but good

The most complete steppe bison specimen ever found is 9,000 years old. It has a complete heart, brain and digestive system, along with near-perfect blood vessels. Some organs have shrunk over time but are remarkable nonetheless.

Frozen foal

A two-month-old horse was found buried approximately 100 metres deep in a Siberian crater. In life it stood almost one metre tall, and its hooves are still intact, along with tiny hairs that are still visible inside the foal's nostrils.

Rebuilding Notre-Dame

Notre-Dame before, during and after the devastating fire on 15 April 2019

This won't be the first time Paris' famous cathedral has been restored to its former glory

As the inferno engulfed the 850-year-old Gothic Notre-Dame cathedral on 15 April, the world was watching. The despair of Parisians was simulcast to millions of screens across the planet, with the tragedy trending on Twitter. But why is this medieval building a world-renowned landmark?

Notre-Dame (meaning 'Our Lady') is far more than a setting for holiday snaps and postcards. It's an icon of Gothic architecture that houses many amazing artworks and holy relics. While the French kings preferred to be crowned at Reims, Notre-Dame has been witness to many historic events.

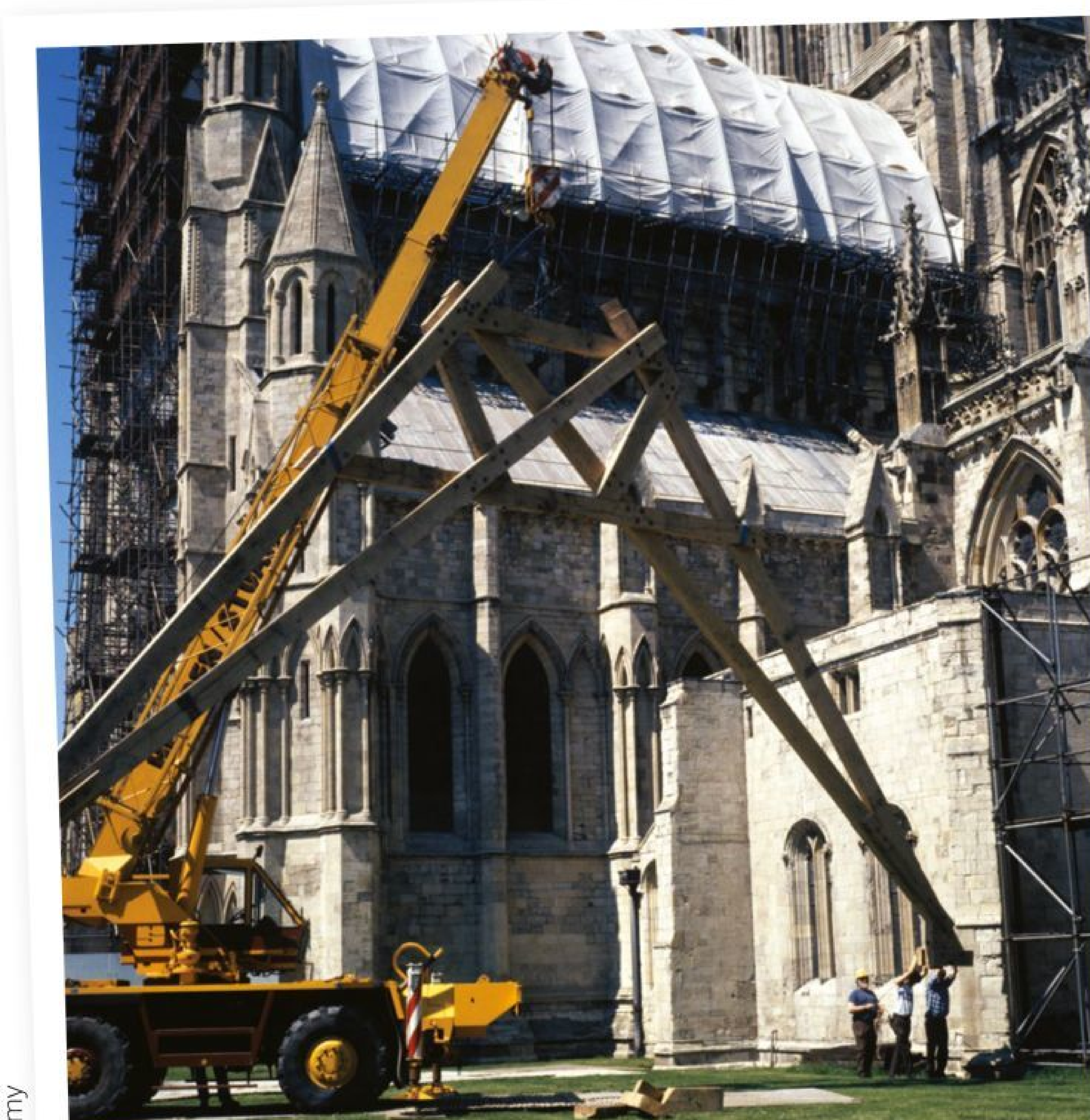
Not that time has always been kind to the cathedral. During the French Revolution, rebels destroyed many of its statues, melted down its bells, and after a brief stint using it as a secular 'Temple of Reason', turned it into a warehouse.

Later in the 19th century, when Paris's medieval ruins were being bulldozed, French author Victor Hugo argued they should be preserved. As well as publishing a pamphlet called *War on the Demolishers!*, he wrote *The Hunchback of Notre-Dame* – simply titled *Notre-Dame* in France.

The story of Quasimodo the cathedral bell-ringer captured the French public's imagination. This led to a nearly 20-year restoration of Notre-Dame, starting in 1844. While architect Eugène Viollet-le-Duc went to great pains to repair the damage, he was later criticised for making his own modifications and using more modern materials, such as concrete, to renovate the spire.

Despite further repairs in 1991, the cathedral was in trouble before this year's fire broke out. Ravaged by pollution, the Archdiocese of Paris believed it would cost over £141 million to restore Notre-Dame. While the fire caused even more damage, an international funding effort quickly began to help raise the cathedral from the ashes. Nearly £780 million was donated in the first 48 hours following the fire.

Craftspeople that helped repair York Minster, which was built 15 years after Notre-Dame, could help with the reconstruction



© Alamy

Notre-Dame 2.0

French President Emmanuel Macron has vowed to rebuild Notre-Dame in time for the Paris Olympics in 2024. But could this be possible? After a fire in 1984, it took four years to repair the damage at the similar-sized York Minster in England.

Of course, many of those who worked on York Minster could lend their expertise to Notre-Dame. New technology could also play a role. Laser scans of Notre-Dame from 2015 contain 1 billion data points. These could be used as a high-resolution 3D blueprint to help reconstruct the medieval structure.

A bigger problem may be finding medieval materials. 5,000 oak trees were used to build the original timber roof. In the 19th century, restorers carefully researched the original location of the ancient quarries used for Notre-Dame's masonry. But with the modern geography of Paris transformed, some of these may now prove very hard to find or impossible to access.

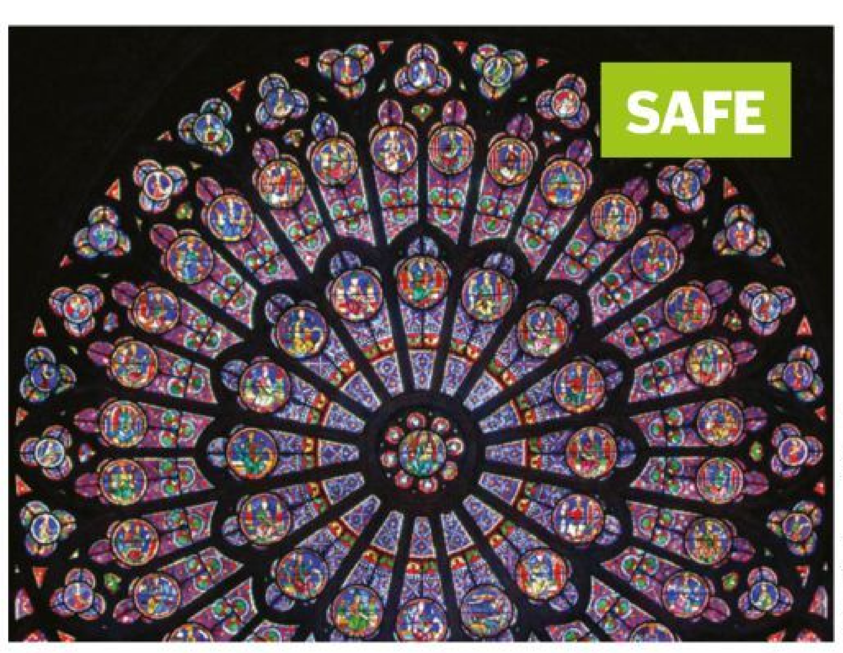
© Getty

York Minster's lead joiner Geoff Brayshaw poses above the roof of the South Transept

The cathedral's treasure trove

Crown of Thorns

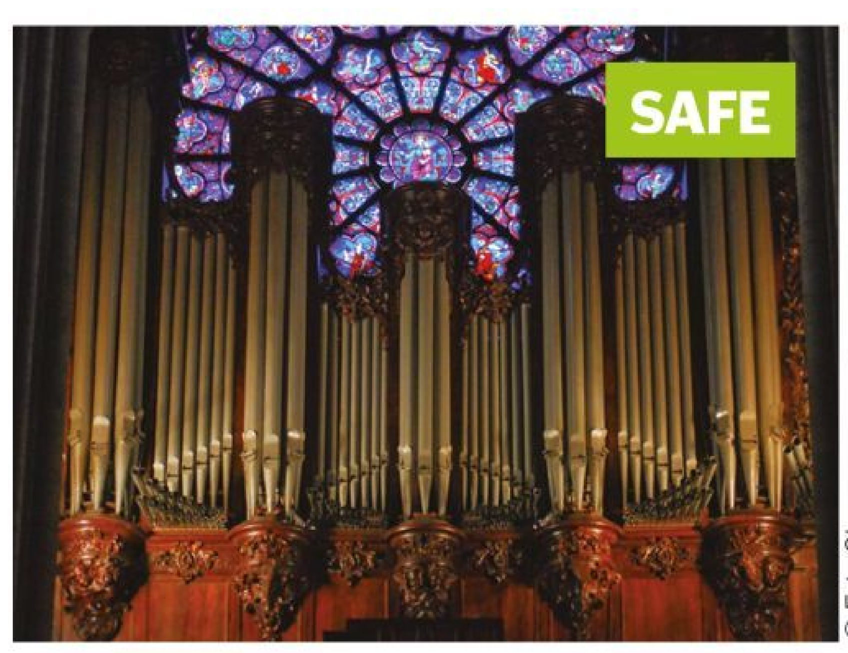
The most precious object in Notre-Dame's collection is believed to have been worn by Jesus Christ. Given to Louis IX in 1238, the thorns are preserved in a reliquary made of gold and crystal.



© Julie Anne Workman

The rose windows

The cathedral's spectacular stained-glass rose windows are made up of petal-shaped panes, each depicting Bible scenes. The west window is the oldest, from 1125, while the south is a huge 12.9 metres in diameter.



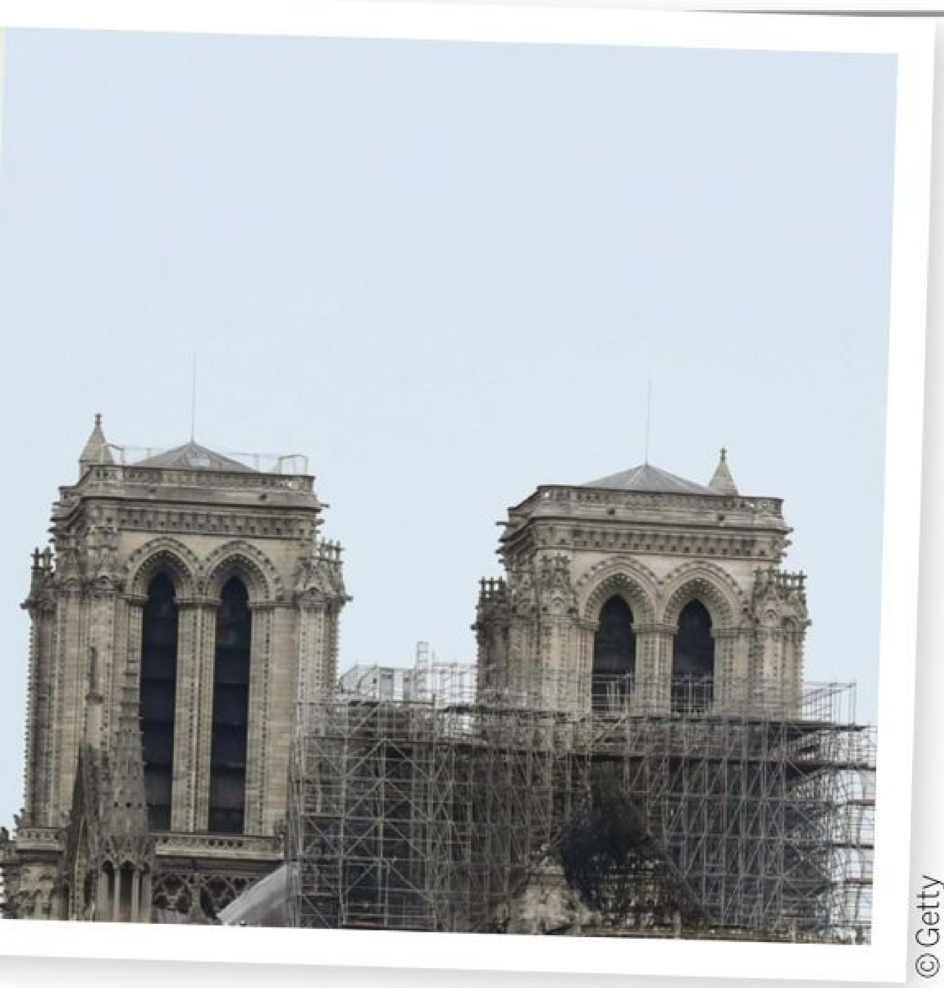
© Eric Chan

The great organ

The largest organ in France, it was rebuilt in the 19th century, but some of its 8,000 pipes date from the 1200s. Organist Louis Vierne played 1,750 concerts before fulfilling his dream of dying at the instrument in 1937.

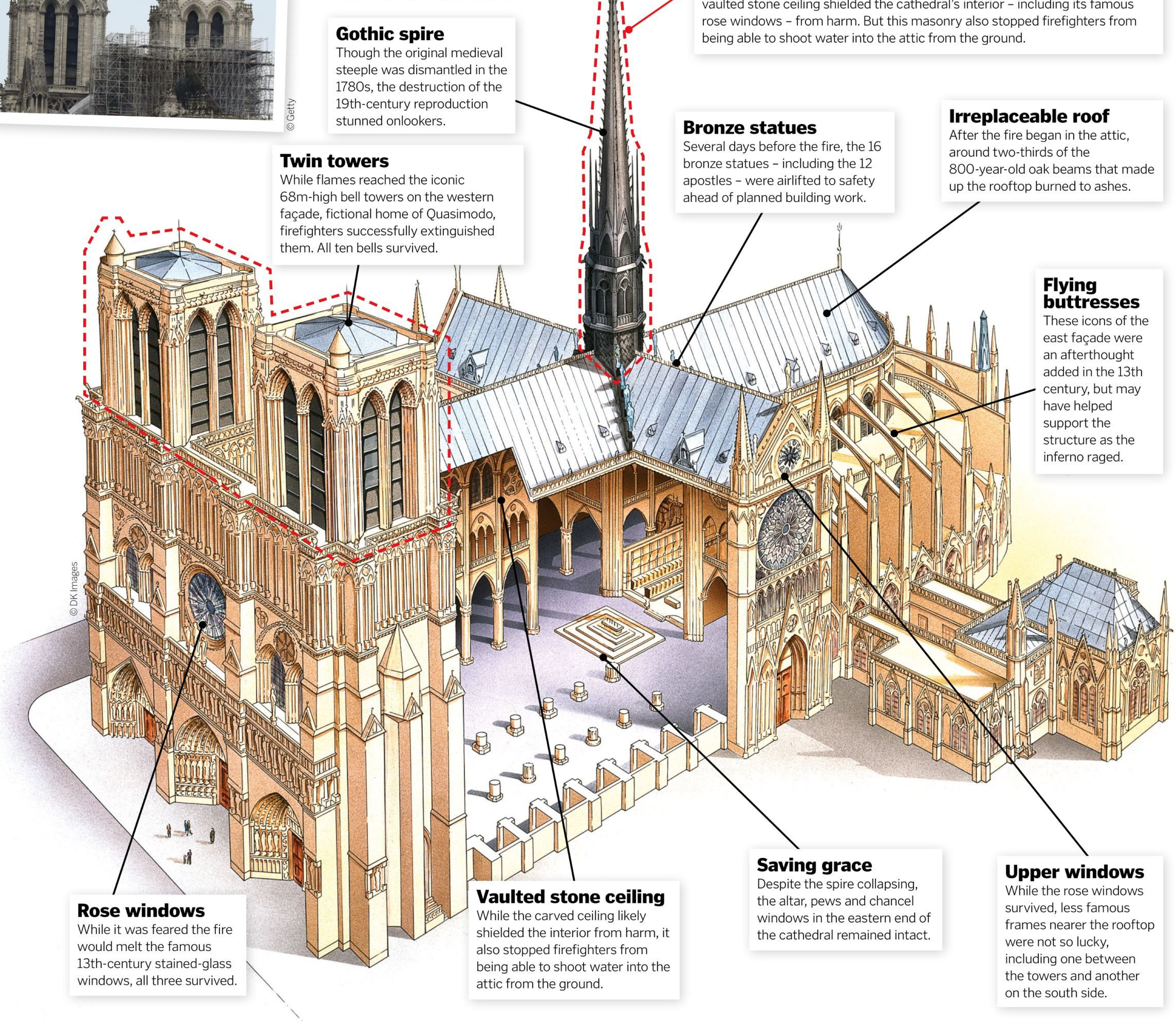
The relics of Saint Denis and Saint Geneviève

Bones, teeth and hair belonging to the patron saints of Paris were destroyed when the spire collapsed. An archbishop had placed them there in 1935 to protect the cathedral.



What was damaged?

The blaze came close to bringing down the medieval marvel



How the fire spread

While it was feared the blaze could level the landmark, the flames were mostly confined to the rooftop. Though the exact cause is still being investigated, the fire began in the cathedral attic. This then ripped through the crisscross of 800-year-old wooden beams, which burned to ash. Possibly stoked by sawdust in the attic, the fire also caused the steeple to collapse. Notre-Dame's vaulted stone ceiling shielded the cathedral's interior – including its famous rose windows – from harm. But this masonry also stopped firefighters from being able to shoot water into the attic from the ground.

Gothic spire

Though the original medieval steeple was dismantled in the 1780s, the destruction of the 19th-century reproduction stunned onlookers.

Bronze statues

Several days before the fire, the 16 bronze statues – including the 12 apostles – were airlifted to safety ahead of planned building work.

Irreplaceable roof

After the fire began in the attic, around two-thirds of the 800-year-old oak beams that made up the rooftop burned to ashes.

Twin towers

While flames reached the iconic 68m-high bell towers on the western façade, fictional home of Quasimodo, firefighters successfully extinguished them. All ten bells survived.

Flying buttresses

These icons of the east façade were an afterthought added in the 13th century, but may have helped support the structure as the inferno raged.

Rose windows

While it was feared the fire would melt the famous 13th-century stained-glass windows, all three survived.

Vaulted stone ceiling

While the carved ceiling likely shielded the interior from harm, it also stopped firefighters from being able to shoot water into the attic from the ground.

Saving grace

Despite the spire collapsing, the altar, pews and chancel windows in the eastern end of the cathedral remained intact.

Upper windows

While the rose windows survived, less famous frames nearer the rooftop were not so lucky, including one between the towers and another on the south side.

The rise, fall and resurrection of Notre-Dame

1163
FOUNDING FATHER
The cathedral's first stone is laid on Paris's Île de la Cité, with Pope Alexander III attending the ceremony.

1185
CALL TO ARMS
Heraclius, archbishop of Caesarea, calls for the Third Crusade from the still-unfinished cathedral.

1431
CROWNING ACHIEVEMENT
During the Hundred Years' War, ten-year-old Henry VI of England is also proclaimed ruler of France in Notre-Dame Cathedral.

1548
RELIGIOUS RIOTING
Rioting French Protestants – known as Huguenots – damage some of the statues in the Catholic cathedral.

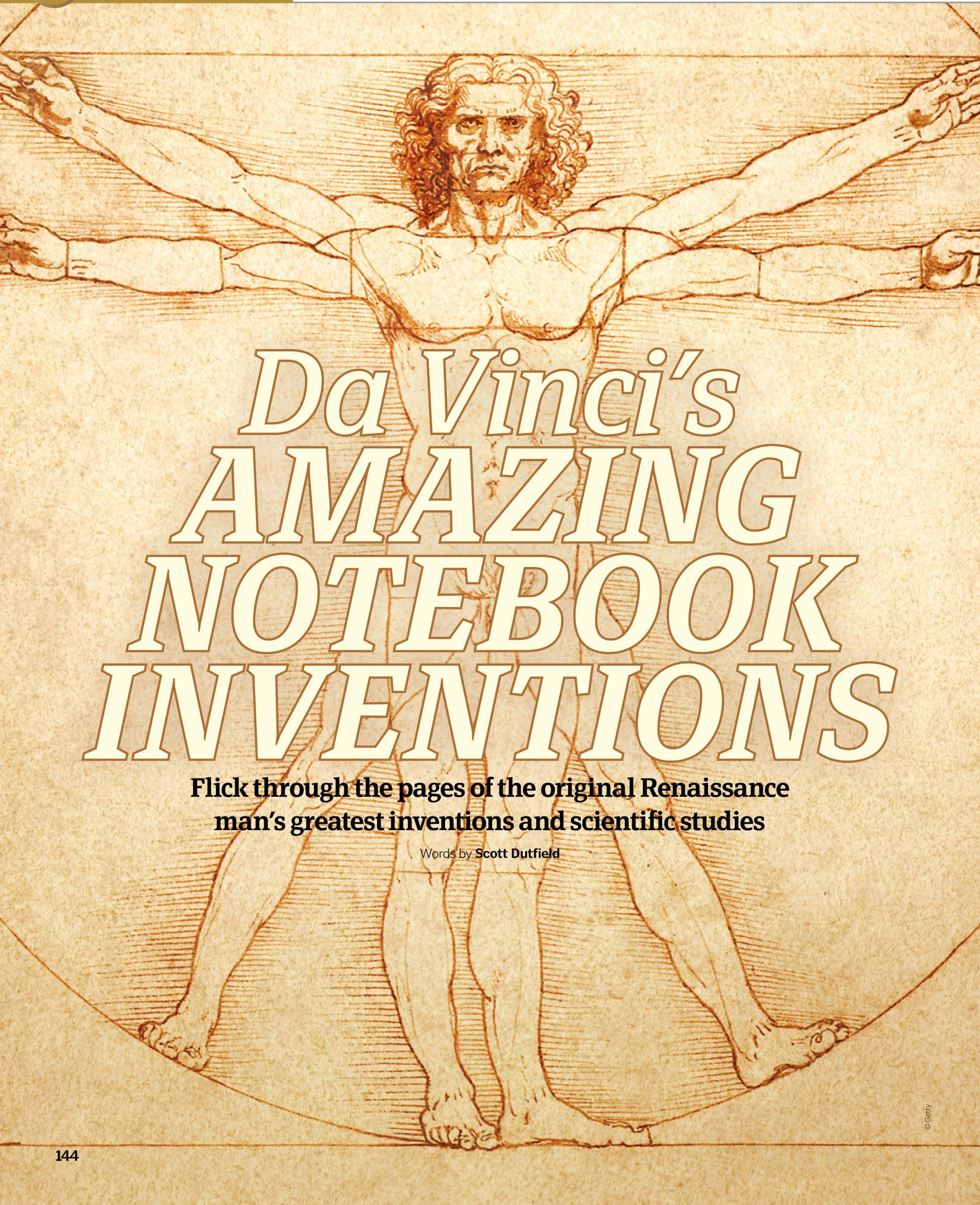
1793
OFF WITH THEIR HEADS
Mobs loot the cathedral during the French Revolution and even decapitate 28 statues of biblical kings in a mock execution.

1804
ALL HAIL NAPOLEON
In a lavish ceremony at the cathedral, watched by a cheering crowd, Napoleon crowns himself emperor of the French.

1844
NOVEL COMEBACK
The popularity of Victor Hugo's *The Hunchback of Notre-Dame* prompts a major restoration of the cathedral.

1871
PARIS IS BURNING
During the Paris Commune insurrection, Notre-Dame is set alight, but it doesn't cause lasting damage.

1914
THE SKY IS FALLING
WWI sees the rise of aerial bombing, but Notre-Dame survives relatively unscathed – except for a hole in the roof.



Da Vinci's AMAZING NOTEBOOK INVENTIONS

Flick through the pages of the original Renaissance man's greatest inventions and scientific studies

Words by **Scott Dutfield**

© Getty

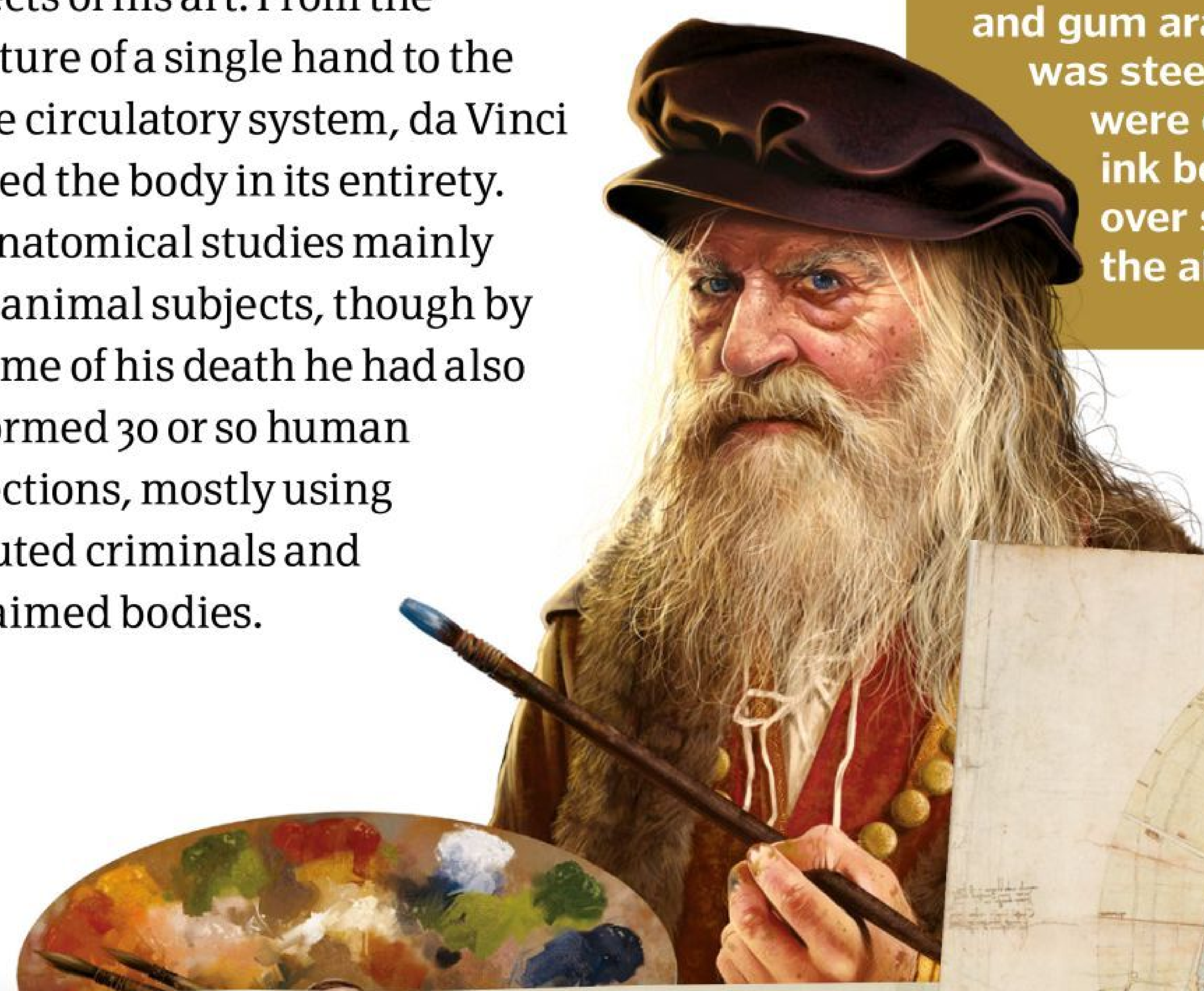
Born in 1452 in Tuscany, Leonardo da Vinci spent his life in the pursuit of knowledge and artistic expression. Now revered for his great works of art, such as the *Mona Lisa* and *Salvator Mundi*, da Vinci's scientific notes suggest his thinking was hundreds of years ahead of his time.

He filled countless notebooks during his career, each bursting with observations about the natural world, the human body and numerous mechanical inventions. One collection in particular, the *Codex Atlanticus*, spans 12 volumes and includes 1,750 drawings.

One of the main focuses in his engineering endeavours, the concept of putting a man in the sky, piqued his interest, and a string of flying machine designs followed. One of his drawings details the design for an 'aerial screw'. Appearing as the ancestor of the modern-day helicopter, this machine was designed to test the air's ability to compress and support human travel in the air. The aerial screw was one of many flying machines conceived by da Vinci, including one that replicated the flapping wings of a bird, but none were made in his time.

Designing multiple other engineering concepts, including weapons, theatrical equipment and hydraulic machines, da Vinci's notes are an inspiration.

Da Vinci is also well known for the study of the human body – both outside and inside. Around the 1480s his attention turned to the study of human anatomy to better understand the subjects of his art. From the structure of a single hand to the entire circulatory system, da Vinci studied the body in its entirety. His anatomical studies mainly used animal subjects, though by the time of his death he had also performed 30 or so human dissections, mostly using executed criminals and unclaimed bodies.



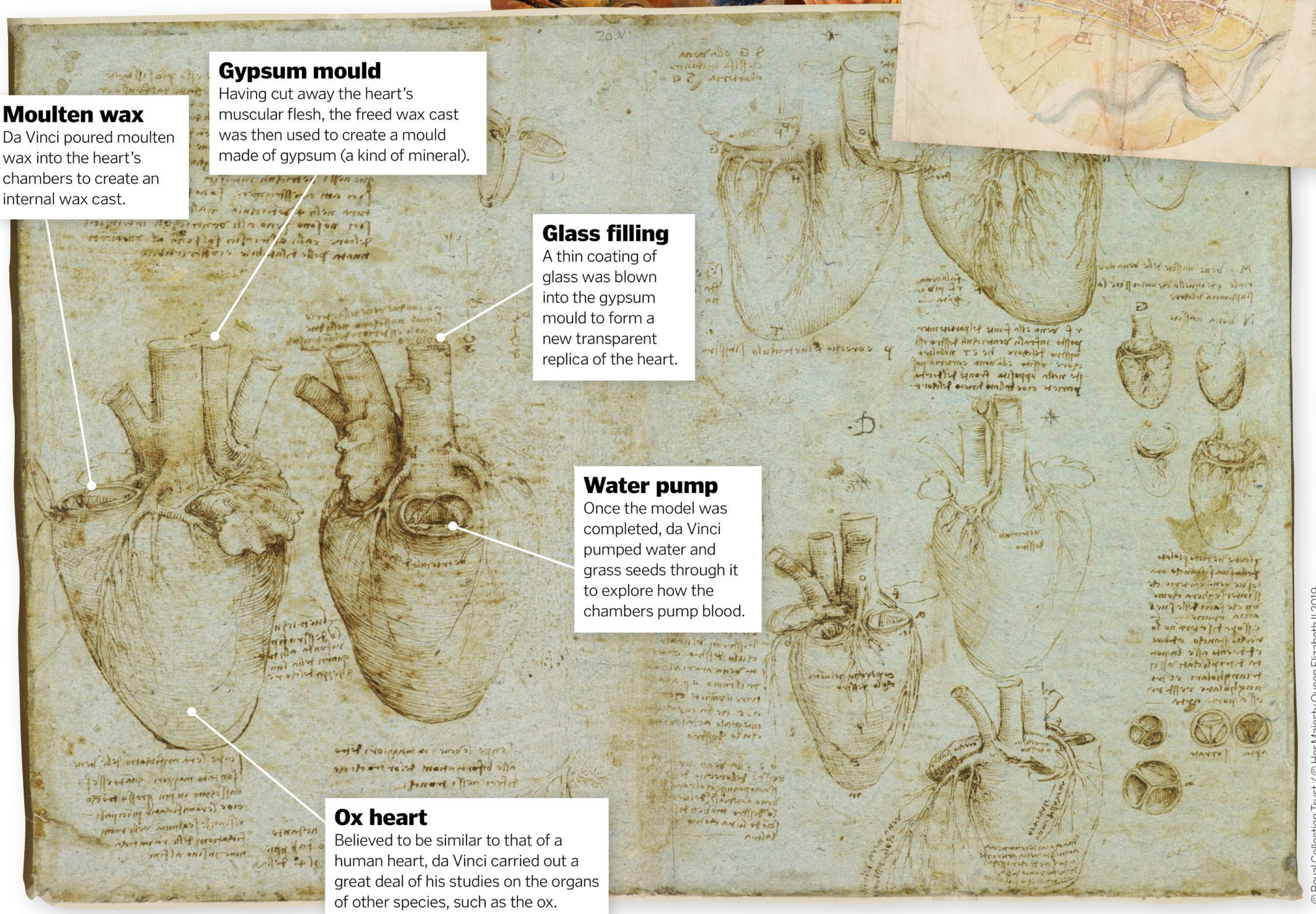
Ink innovation

Made from oak tree galls, iron sulphate and gum arabic, it's a wonder how these three ingredients ever found their way together to produce da Vinci's black ink. At a time when ink was commonly made using home recipes rather than being sold as a product, its manufacture was quite time-consuming. Crushed in a cloth, the oak galls were soaked in rainwater and boiled. The resulting liquid was then strained and combined with iron sulphate and gum arabic. This creative concoction was steeped until all the ingredients were completely dissolved. The final ink began as a pale violet grey, but over several days the exposure to the air turned the ink black.

In his notes, da Vinci mapped the city of Imola, Italy, after being named general architect and engineer to Cesare Borgia, c. 1502

Making a heart of glass

In order to study the inner workings of the human heart da Vinci created a glass model to test his theories



Seeing the invisible

Over time the work of da Vinci, like that of many other artists, becomes vulnerable to damage from light, atmospheric or physical erosion. However, with the help of ultraviolet (UV) light previously unseen work can be brought back to life. This was the case with a set of hand drawings da Vinci had completed as studies for his painting *Adoration of the Magi*. Invisible to the naked eye, these seemingly blank pieces of paper revealed the illustration when illuminated with UV light. This was due to the type of ink da Vinci used. Under UV light certain materials, such as paper, luminesce (glow). The iron-rich ink, though faded, blocks the luminescence, revealing the hidden images on the page.

These drawings of hands, invisible under normal conditions, are illuminated under UV light. They were a study in preparation for *Adoration of the Magi*, created c. 1481

Seen in his surviving notes and anatomical drawings, da Vinci made waves with his near-accurate description of the human heart. Using his characteristic resourcefulness, da Vinci set to work creating a glass heart from that of an ox. He then not only noted its appearance in detail but proceeded to put his theory of its function to the test.

By pumping water through the glass da Vinci deduced that there were vortices (a strong movement of blood) in the heart's chambers. This motion was responsible for the closure of the heart's valves after each pump of blood. Incredibly, it wasn't until the introduction of real-time MRI scanners that da Vinci's work was confirmed as accurate.

"Had he not done anything else in his career, had he not painted a single thing, this would have still marked him out as being one of the great figures of the Renaissance, certainly one of the greatest scientists, both in the depth and the range of his work on human anatomy," explained Martin Clayton, head of prints and drawings for Royal Collection Trust at Windsor Castle and a specialist in the drawings of Leonardo da Vinci.

Da Vinci's scientific studies, however, didn't always bear the fruit of scientific discovery, and the results of many of his endeavours often left him scratching his brilliant head.

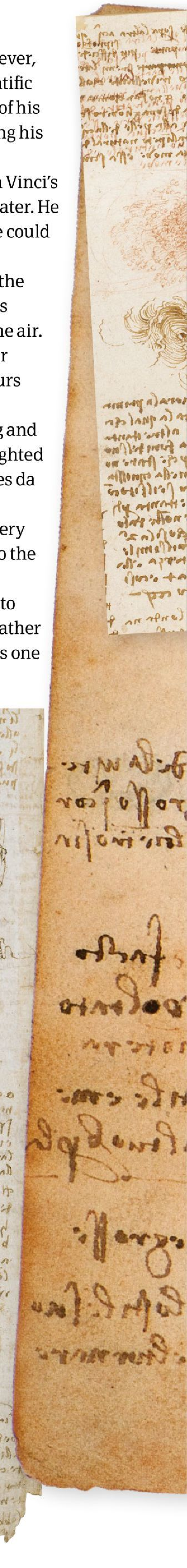
In the later years of his career, da Vinci's notes turned to the movement of water. He thought that by observing water he could understand the basis of force and movement. His extensive notes on the subject of water worked to codify its movement and interactions with the air. He drew the eddies and the circular motions that occur when water pours into a pool, for example.

However, unlike his engineering and anatomical work, this study highlighted some of the fundamental difficulties da Vinci faced.

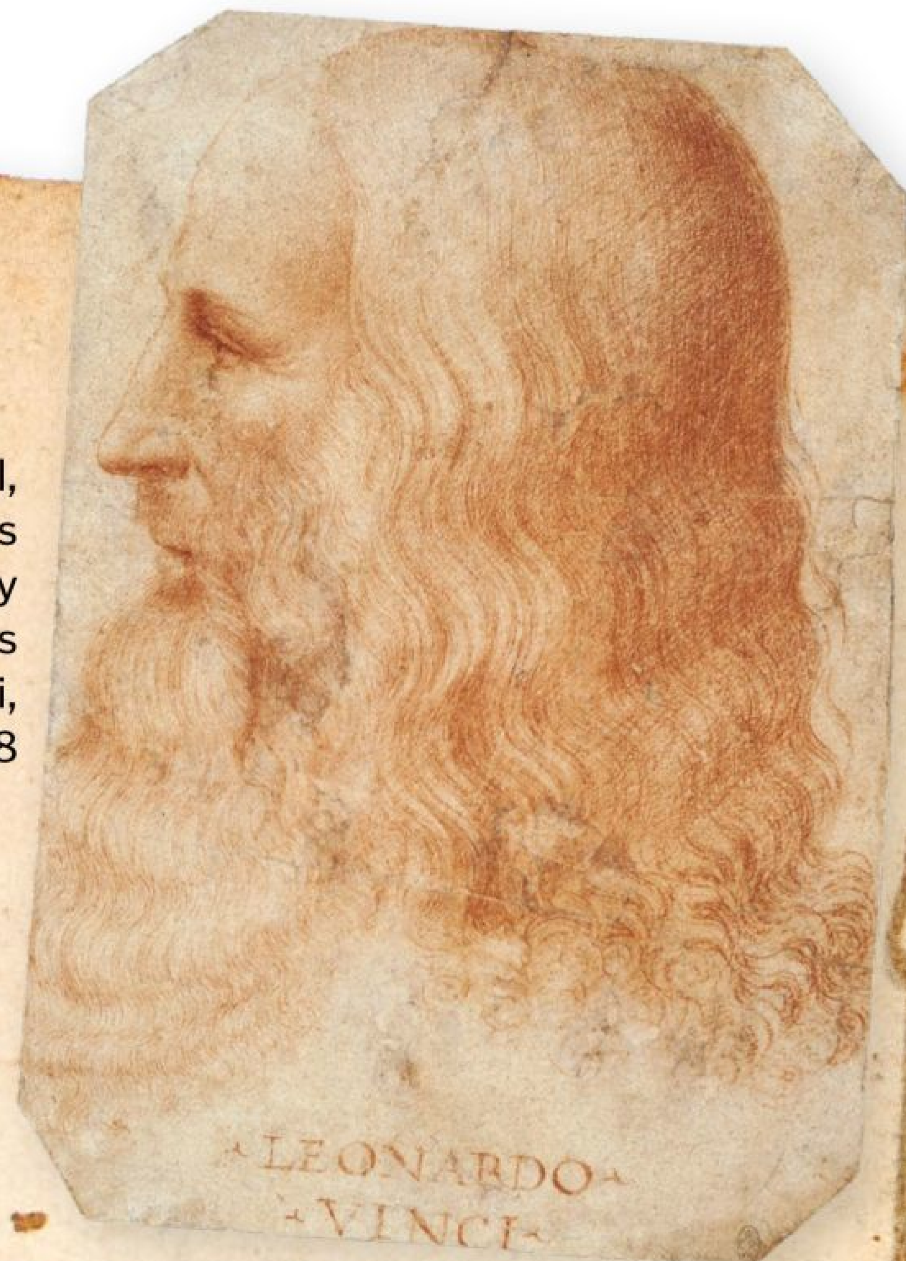
"Leonardo as a scientist finds it very difficult to move from the specific to the general," notes Martin Clayton.

"His scientific observations tend to restate endless specific examples rather than overarching principles. That is one of his downfalls as a scientist."

Da Vinci drew a human embryo within a human uterus with a cow's placenta, believing that mammals shared a common anatomy, c. 1511



In studies of water, da Vinci noted its movements in relation to physical law, c. 1510–12



Drawn by his pupil, Francesco Melzi, this is one of the only remaining portraits of Leonardo da Vinci, c. 1515–18

Leonardo's aerial screw

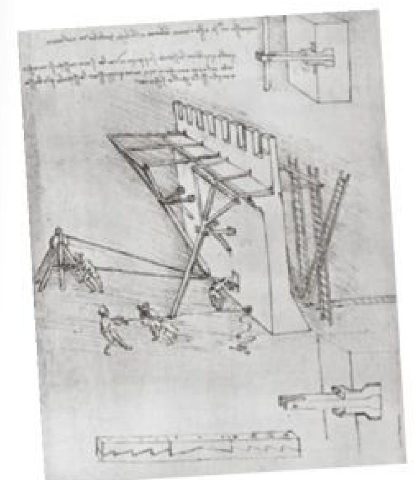
One of da Vinci's many inventions, the aerial screw was designed to fly like a modern-day helicopter

Wing structure
Designed to have an iron frame, wooden ribs and linen covering, this helical structure was supported by a central wooden mast and reinforced with tension lines.

Pilot deck
At the base of the aerial screw was a platform or 'pilot desk' split in two – one stationary base and another that rotated with the spiral wing.

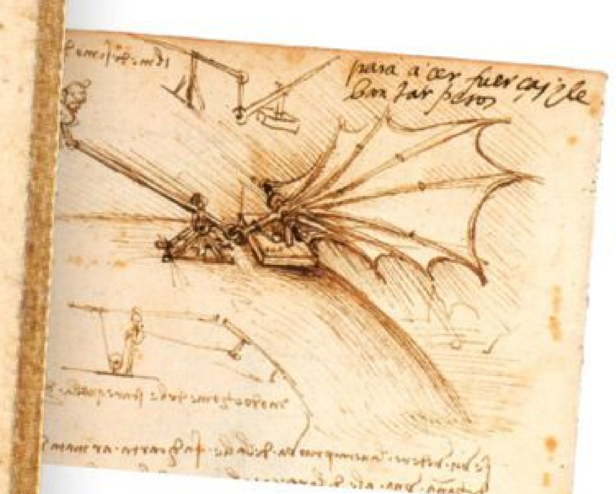
Flying
As the pilots turned the operating tiller in the centre of the structure, the spinning spiral wing was hypothesised to bore its way into the air like a screw into wood.

Da Vinci's inventions through the years

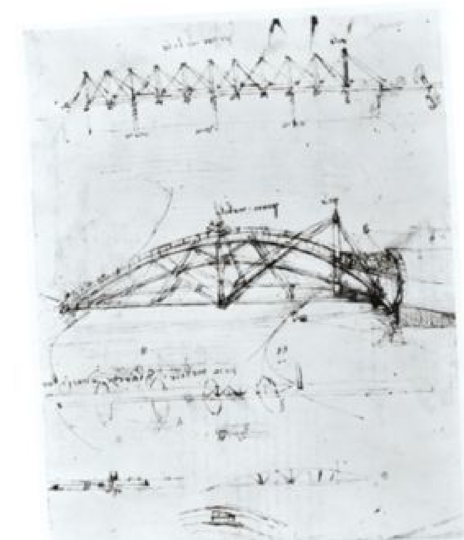


1482–1485
Wall defence
Through a series of levers and beams, da Vinci devises a system to push the ladders of opposing forces away from defensive walls.

1485
Armoured car
This vehicle is protected by a giant shield, with a series of cannons mounted around the circumference. Fitting a horse inside to drive it would prove impossible.



1487–1489
Flapping wing
To test out his theories of human flight, da Vinci sketches a flapping wing apparatus and a counterweight to see how moving the wing could lift weight.



1487–1489
Swing bridge
Da Vinci notes down three studies of bridges, including a swing bridge and a floating bridge, though the designs never leave the pages of his notebook.

1504
Bombards
Intended for presentation to a patron and not part of his unique studies, these gunpowder-fuelled exploding cannonballs are designed to release deadly wedge-shaped iron pieces.

1513–1514
Dredger
During the last few years of his illustrious life, Leonardo da Vinci designs a man-powered dredger that can scoop mud from water systems in order to prevent overflowing.

The pillars on which Lincoln's hands rest are fasces, wooden bundles associated with power

Approximately 40% of the Lincoln Memorial is located underground

The Lincoln Memorial

Why was the 16th president honoured with a memorial that looks like a Greek temple?

Strength, wisdom, fortitude – for many, United States president Abraham Lincoln embodied all those qualities, so when he was brutally assassinated in 1865, plans for a memorial in his honour began immediately. However, years of disagreement over the project meant that construction didn't commence for nearly 50 years.

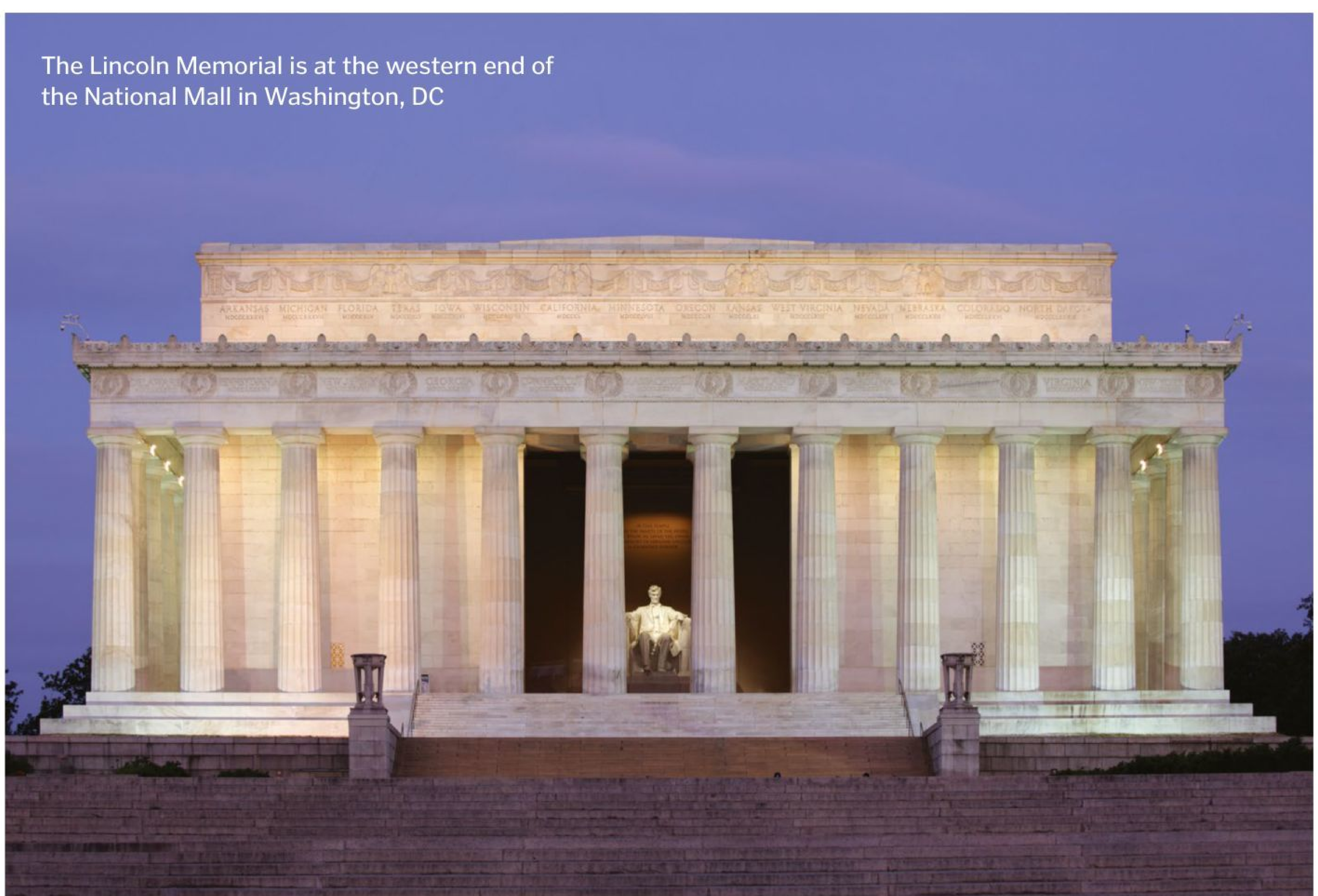
The finished temple-like building stands at 30 metres (98 feet) tall, a dominating feature of the nation's capital, Washington, DC. Architect Henry Bacon drew inspiration for his design from the Parthenon in Athens. He felt it was fitting to honour a man who defended democracy with a structure from the very birthplace of democracy. And the symbolism doesn't end there. The building's 36 columns represent the states of the Union at the time of the president's death, with the entire memorial constructed from stones from different parts of the United States to convey the importance of the Union to Lincoln.

The enormous statue of the man himself was carved from Georgia marble and took four years to complete. It was designed by Daniel Chester French, who studied photographs and eyewitness accounts from the Civil War to get the facial expression just right. The statue sits in the central hall, which is separated from two other chambers by rows of columns. More than just decorative, these provide structural support for the ceiling.

Great care had to be taken to ensure the walls and foundations were strengthened, due to the marshy terrain. The ground had to be drained and filled, and 122 solid concrete piers (cylindrical columns) with steel reinforcements were rooted into the bedrock. Above that is a second series of piers, joined together with concrete arches to form the memorial's floor. More supports were added when the Lincoln statue doubled in size to 5.79 metres (19 feet).

In 1922 the memorial opened to the public as a shrine, a museum and a place of pilgrimage for millions of visitors.

> *"The 36 columns represent the states of the Union at the time of the president's death"*



The Lincoln Memorial is at the western end of the National Mall in Washington, DC

Murals and meanings

Behind the larger-than-life Lincoln statue are the words, "In this temple, as in the hearts of the people for whom he saved the Union, the memory of Abraham Lincoln is enshrined forever." Written by *New York Herald Tribune* art critic Royal Cortissoz, the inscription sums up the purpose of this impressive structure. This is accompanied by inscriptions of two of the president's most famous speeches on the north and south walls.

The Gettysburg Address was delivered during the American Civil War in 1863 and showed the president's determination to reunite the nation. The other is the Second Inaugural Address – delivered in 1865 just before the end of the Civil War – which asked people of the Union to show "malice towards none; charity for all." Above each inscription is a large mural painted by Jules Guérin. They depict the Angel of Truth releasing slaves and joining the hands of two figures in unity respectively. The paint was mixed with kerosene and wax to protect them from the temperature and moisture, preserving them for years to come.

Part of a mural above the Gettysburg Address in the Lincoln Memorial

The ceiling tiles were made from Alabama marble and soaked in paraffin to turn them almost translucent

Tiger tank anatomy

A still from a Nazi propaganda film showing a formation of Tiger II tanks

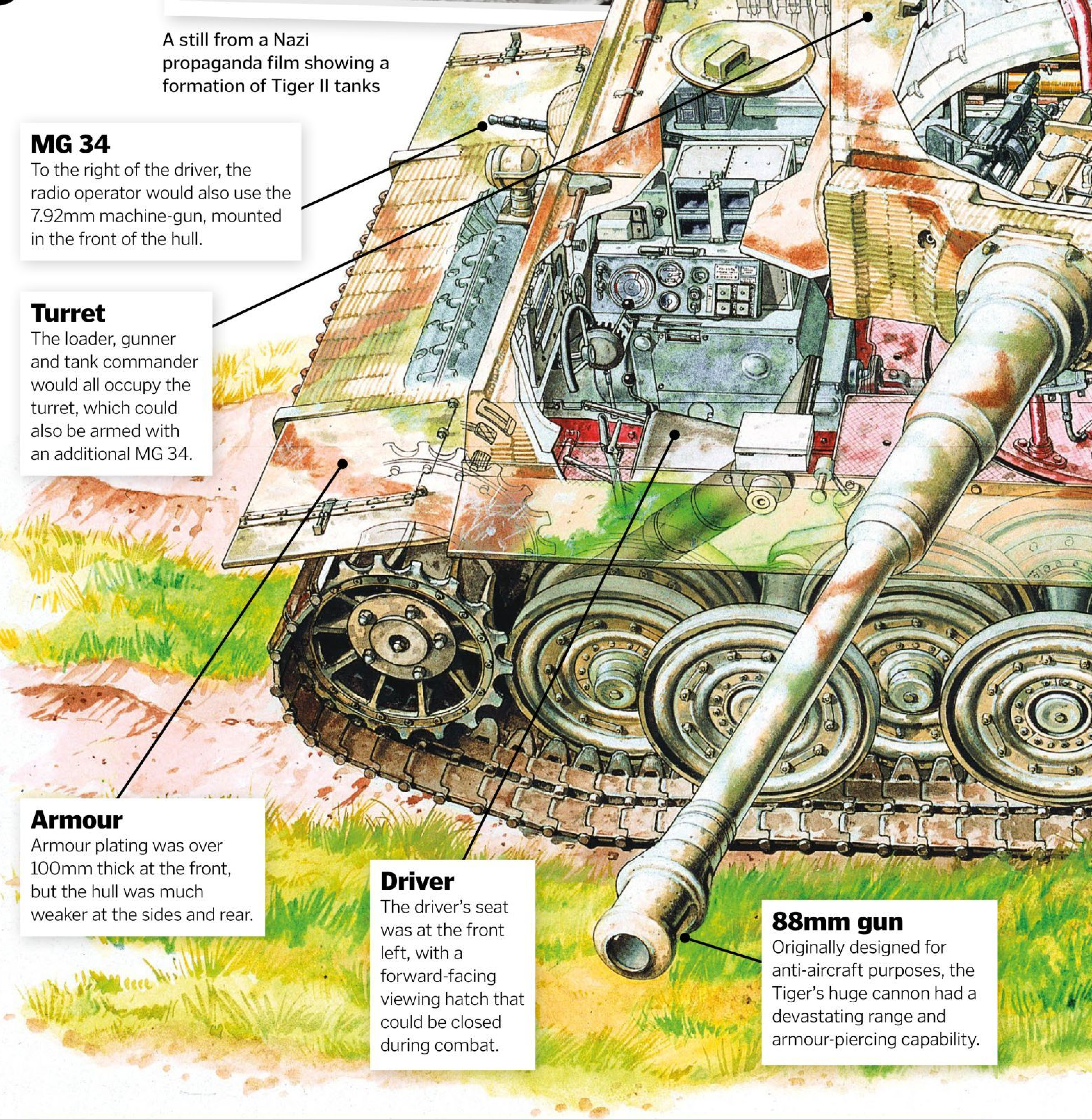
Nazi Germany's ultimate heavy panzer was designed to strike a decisive blow for the Third Reich

The Panzerkampfwagen VI, more commonly known as the Tiger I, was developed in the early 1940s with the aim of creating an unstoppable armoured killing machine for the German military. Two rival engineering companies, Porsche and Henschel, were approached to produce prototypes for the tank, meeting specifications such as weight, cost and weapon capability. Henschel's design was eventually selected and rushed onto the production line in order to quickly deploy on the Eastern Front, joining Hitler's ongoing invasion of the Soviet Union.

It took five crewmembers to operate the Tiger: a driver, gunner, loader, commander and radio operator. The tank's main weapon was a 88mm gun, which was originally designed as an anti-aircraft artillery piece. At the time of the Tiger's first deployment, this huge cannon was capable of penetrating any enemy armour from long range. Years after its first deployment, during the Battle of Normandy in 1944, this enabled Tiger crews to ambush Allied formations from a distance, unleashing devastating fire before their enemy had a chance to respond.

The Tiger's armour was 100mm thick at the front – strong enough to stop or deflect nearly any Allied return fire. Battlefield accounts of Tigers in combat report round after round of enemy fire failing to penetrate its formidable shell. Unlike another prolific German tank, the Panther V, the steel plate protection of early Tigers was not angled, which provided less protection. This angled design feature was later added to the King Tiger, which was completed in the final months of the war – too late to prevent the defeat of Nazi Germany.

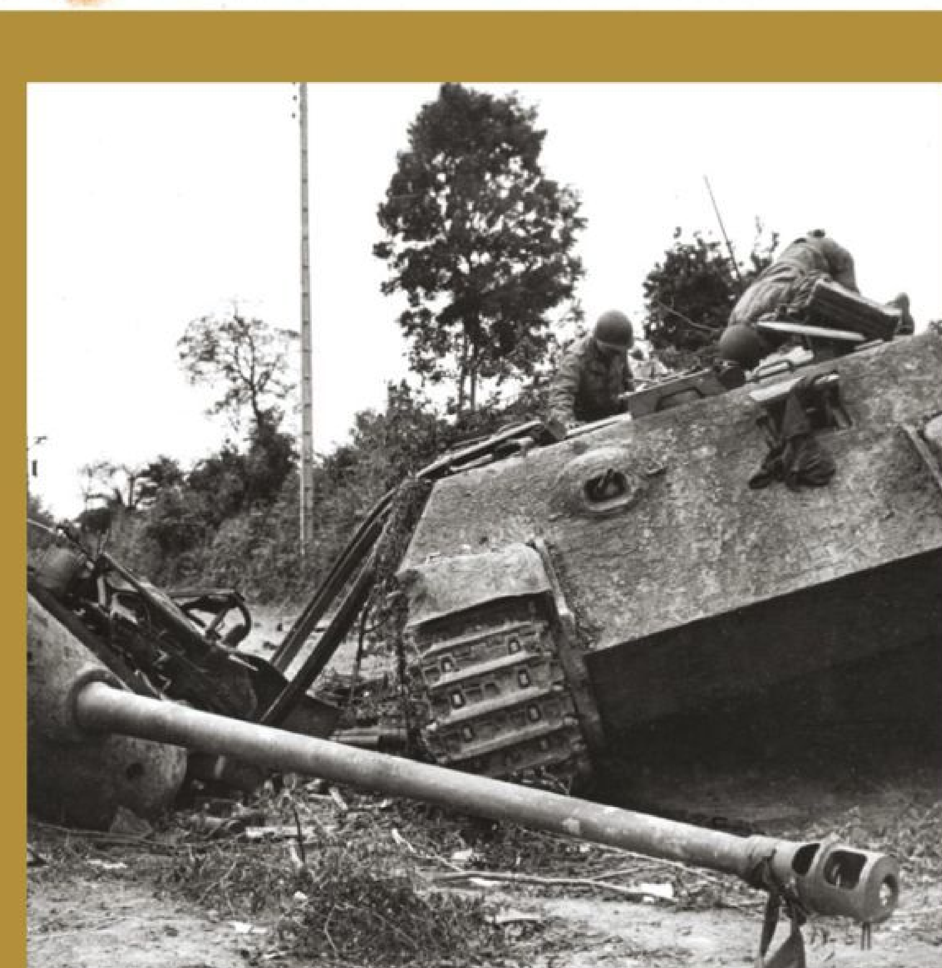
Despite its fearsome reputation on the battlefield, the Allies were eventually able to counter the Tiger I's capabilities, outnumbering, outmanoeuvring and eventually outgunning the once-dominant machine. Today, the Tiger remains among the most iconic vehicles of WWII and a milestone in the history of armoured warfare.



A paper Tiger?

Although the armour and weaponry of the Tiger posed a formidable threat on the battlefield, the tank never struck the decisive blow so desperately desired by the German high command. Among the main challenges to the Tiger was the number that could be deployed. Germany's military factories became targets for Allied bombers, and key components for the tank's production became delayed, meaning fewer were ready to join the front line than expected.

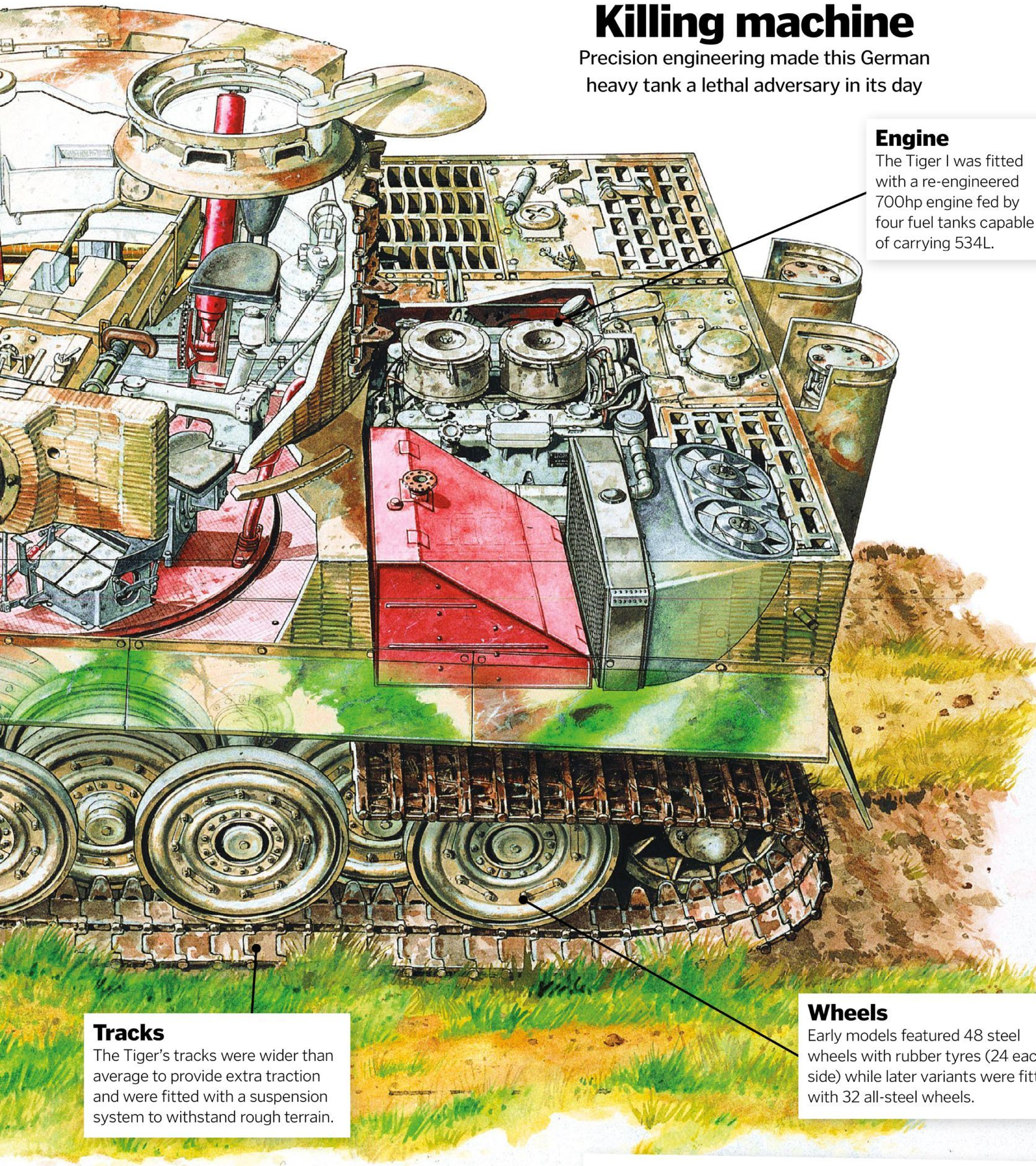
In addition, the tank's size and complexity, including the innovative suspension system, made it much more expensive and time-consuming to produce. High fuel consumption was also a major drawback to the tank's effectiveness, meaning it only had an off-road range of up to 110 kilometres.



A destroyed Tiger II 'King Tiger': production costs also hamstrung the Tiger's successor

Killing machine

Precision engineering made this German heavy tank a lethal adversary in its day



Engine
The Tiger I was fitted with a re-engineered 700hp engine fed by four fuel tanks capable of carrying 534L.

Tracks
The Tiger's tracks were wider than average to provide extra traction and were fitted with a suspension system to withstand rough terrain.

Wheels
Early models featured 48 steel wheels with rubber tyres (24 each side) while later variants were fitted with 32 all-steel wheels.

Evolution of German armour

PANZER I
1934
Small, nimble and lightly armed with two machine-guns, these tanks were manned by just two crew members.

PANZER IV
1937
Fitted with a 75mm turret cannon, this was the most numerous German tank during WWII, with over 8,000 produced.

TIGER I
1942
With a huge 88mm gun, the Tiger I favoured firepower over the greater manoeuvrability of the Panther.

PANZER V PANTHER
1943
Developed to tip the balance on the Eastern Front, its sloped armour plating increased its effectiveness against horizontal ballistics.

TIGER II
1944
The King Tiger combined the effective sloped armour of the Panther with an improved 88mm cannon.

PANZER VIII 'TIGER MAUS'
1944-5
The 'super heavy' Tiger II successor would have carried a 128mm cannon with 250mm sloped armour. The project was never completed.

Other big cats

Although the Tiger I was the most numerous and notorious of Nazi Germany's heavy tanks, several other versions were also developed to tackle specific combat scenarios. The Panzerjäger Tiger, or 'Elefant', was a tank destroyer based on the chassis of a Tiger but designed to hunt down enemy vehicles. The Elefant featured a fixed turret, meaning that it could not rotate to adjust its aim, and its 88mm gun therefore stretched out across the front of the chassis, resembling an elephant's trunk.

Another short-lived Tiger variant was the Sturmtiger, an assault gun that was developed with one job in mind – to demolish anything and everything that stood in its way. Armed with a massive 380mm cannon, the Sturmtiger fired rocket-propelled shells that could lay waste to massed enemy positions or even obliterate buildings. Only 19 Sturmtigers were ever developed, making them another curious but small footnote in the history of the Tiger tank.

The Elefant featured a fixed 88mm gun on a Tiger chassis and was deployed as a tank destroyer

WHAT THE DINOS REALLY LOOKED LIKE

SAURS

HOW INCREDIBLE NEW DISCOVERIES ARE BRINGING THESE PREHISTORIC BEASTS BACK TO LIFE

Words by **Amy Grisdale**

The reign of the dinosaurs began just after the biggest mass extinction Earth has ever seen. 70 per cent of land animals and 96 per cent of marine species were obliterated in a mysterious cataclysmic event around 250 million years ago. Evidence shows this Permian-period extinction happened in phases. It could have been a series of giant meteor impacts or an increase in volcanic activity that caused fires and explosions worldwide. It's also possible a sudden surge of methane from the ocean floor brought about abrupt climate change.

© Getty / EOFAUNA

The most complete T. rex skeleton we've found is named Sue. It is over 90 per cent complete

© Chase Elliott Clark

The remains of an Oviraptor were found near a nest (they were thought to eat eggs), but in this case it was actually defending its own clutch

© HombreDHojalata

Whatever happened, it appears to have been quick. The surviving animals entered a new geological era, during which they would go on to dominate the planet. Vegetation exploded in the absence of so many animals, and after a period of 10 million years conditions were just right for new species to thrive. A group of reptiles called archosaurs took control and began to adapt to their new surroundings in the middle of the Triassic period. Dinosaurs of every shape and size roamed the Earth for the next 170 million years, from the crow-sized Microraptor to the blue-whale-sized Argentinosaurus. The last dinosaurs died out in the most recent mass extinction that paved the way for humans to evolve. Their fossilised remains lay buried for millions of years before humans even existed.

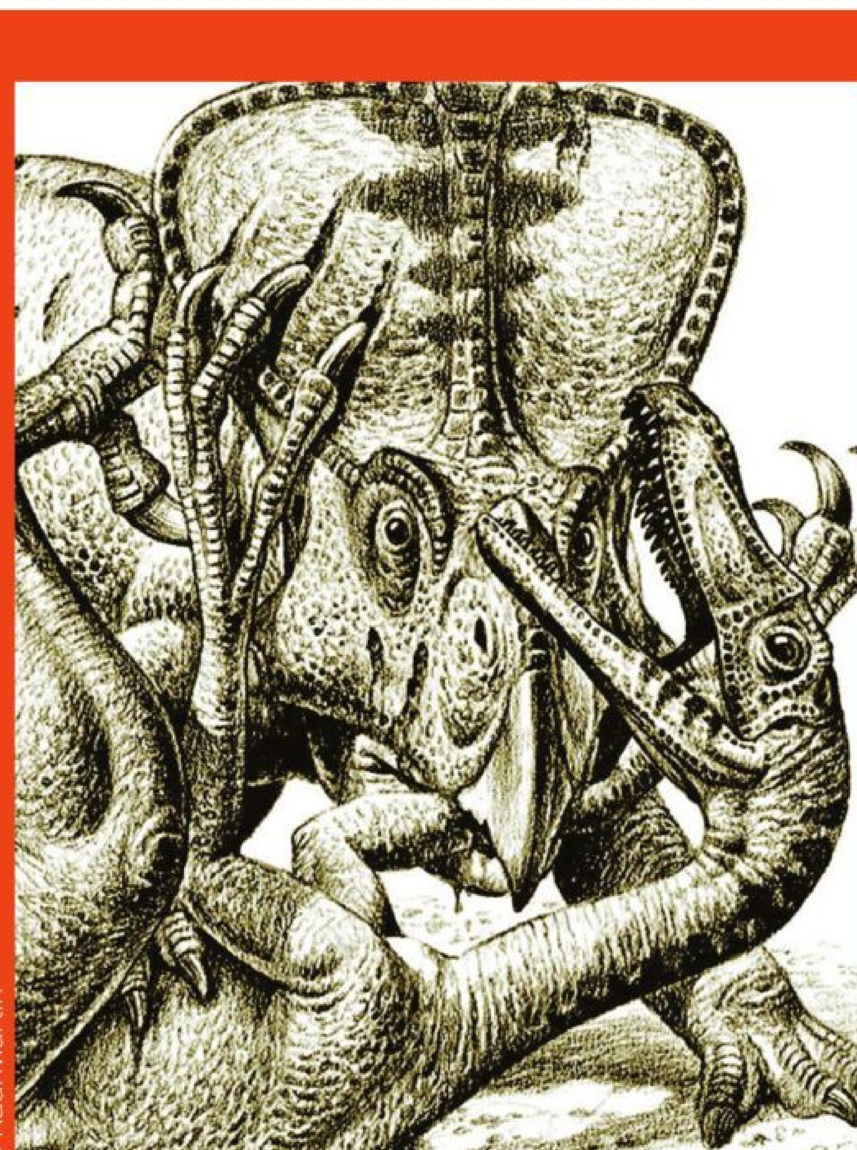
Dinosaur remains weren't recognised for what they truly were until 1824. Oxford University professor William Buckland studied bones that had been discovered some 150 years earlier by naturalist Robert Plot. While Plot was convinced they were remnants of a race of giant humans, Buckland knew they must have been from some kind of carnivorous lizard. He called his new discovery Megalosaurus – 'great lizard'.

"Dinosaurs of every shape and size roamed the Earth for the next 170 million years"

In the 19th century new discoveries were met with some scepticism. Amateur fossil collector Mary Anning found the first complete plesiosaur skeleton in 1824, but experts had their doubts. Georges Cuvier was famous for founding the study of vertebrate biology and gave his name to over 50 animal species that are still alive today. He voiced his concern that the find was a hoax. He was certain there were too many bones in the neck for the animal to hold it up and suspected the fossil was two species fused together.

The Geological Society agreed that something dubious was going on and called a meeting to

Prehistoric forensics



© Raul Martin

Dinosaurs were fast healers and survived injuries that would have been deadly to the average mammal

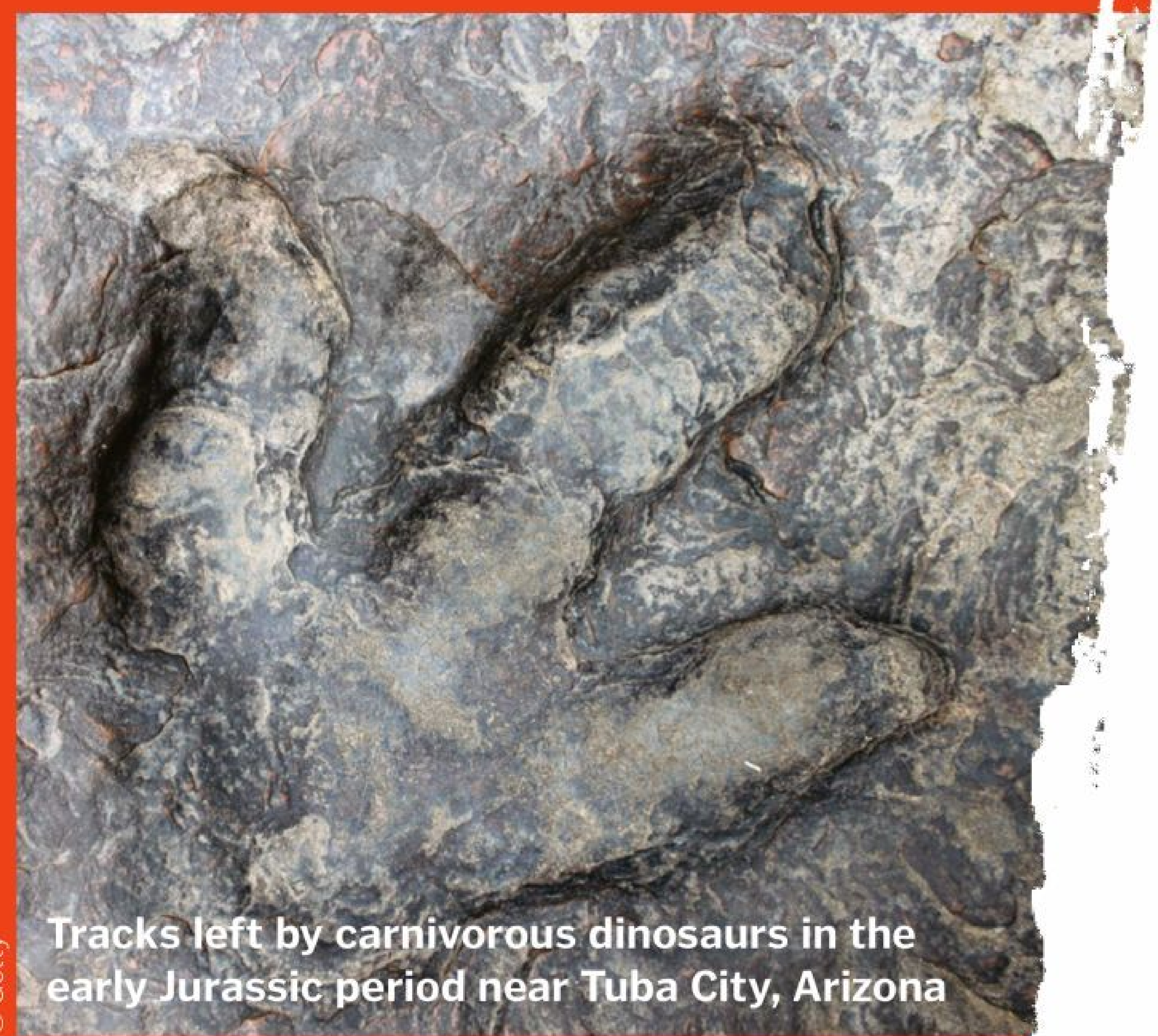
We can determine the cause of a dinosaur's death by examining bones, footprints, skin, teeth and eggs. Physical trauma could be fatal, such as damage inflicted by another animal. Fights must have been brutal. A fossil of the theropod *Allosaurus fragilis* found in Wyoming, US, in 1991 had 19 fractures. Another was uncovered five years later with 13 damaged bones literally from head to toe.

Bone diseases could cause death through deformities, tumours and infections. We can even recognise healed fractures and identify what species left tooth marks in fossils. Remains with a rough texture indicated the animal suffered a degenerative disease. A virus that originated among the dinosaurs may be responsible for hepatitis B today.

There are conditions that dinosaurs had when they died that were not necessarily the cause of their demise. Several specimens had infected or missing toes, and trace fossils show animals limping. Dinosaurs even got ticks and fleas.

Finding footprints

Dinosaurs left impressions in mud that could harden into stone. We measure their dimensions, but there is more information hidden in a trace fossil. We can glean skin texture, the length of their strides and even deduce complex behaviour like building nests. Footprints left by an Eubrontes 200 million years ago, found in modern-day North America, were startlingly similar to modern birds. They show a sequence of a dinosaur stopping for a rest by the lake. There are footprints leading to a divot created when it squatted down, then steps leading away while the tail dragged on the ground.


Tracks left by carnivorous dinosaurs in the early Jurassic period near Tuba City, Arizona

© Getty


Measuring the vertebrae of the giant sauropod Futalognkosaurus, the most complete of its kind discovered to date

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The story of bones

Bones give us huge clues about a dinosaur's size, posture and locomotion. Scientists can reconstruct muscle and cartilage by examining marks on bones. Erosion to the teeth tells us what the animal ate. CT scans build up 3D images of bones by taking panoramic X-rays. We've found that a great deal of dinosaur bones contained air sacs like birds do. Using this technique we are able to figure out how old a dinosaur was when it died, what its skin looked like and even the size of its brain. Muscles and skin can be layered onto reconstructed skeletons in order to create accurate pictures of long-dead dinosaurs.

Signs in skulls

A dinosaur skull is a goldmine. It contained the eyes, mouth, nose, ears and brain of the animal. We have learned an incredible amount about dinosaurs by studying their skulls.

Scientists digitally recreated a T. rex skull and rebuilt the muscle by researching the jaws of birds and crocodiles. They found it had a bite force of about 5,800 kilograms, the hardest bite of any terrestrial animal in history. The muscles responsible for closing the jaws grew exponentially when the animal matured and were extremely large, even for such a big animal. This figure is not agreed upon by all dinosaur researchers though.

We know that Spinosaurus was adapted for swimming because of the position of its nostrils. They were far back on the top of the narrow skull, a lot like a crocodile's. It was probably bigger than T. rex judging by the length of the snout, possibly reaching 16 metres long.

Q&A

The big dino questions

We spoke to Eofauna's dinosaur experts about how they create accurate models of these extinct creatures

What can fossils tell us about a dinosaur and its appearance?

It depends heavily on the quality of fossil data. The more complete the remains are, the more accurate the dinosaur representation will be. If a skeleton is fairly complete, we can restore the shape of the animal accurately. This requires adequate knowledge of comparative anatomy for reproducing good digital reconstructions of muscles and bones. We usually use modern birds, but distantly related animals like elephants are useful for sauropods in terms of biomechanics and posture.

Did most dinosaurs have scales or feathers?

All dinosaurs had scales but some, especially the most advanced theropods, also possessed feathers. Only a few species had developed secondary feathers. Dinosaurs probably all had simple developing feathers we call filaments.

Can we be sure what colour a dinosaur was?

No. Apart from a very few cases where melanosomes have been preserved, we can only speculate. Colours can be estimated from the animal's lifestyle, size and the climate they inhabited.

Asier Larramendi and Rubén Molina

Scientific directors at Eofauna

Asier and Rubén are the founders of Eofauna, a company that creates scientifically accurate representations of prehistoric fauna. Asier's work focuses on the comparative anatomy, body size, biomechanics and functional morphology (shape) of extinct vertebrates. Rubén specialises in biogeography, biometrics, ichnology (footprints) and bibliographic documentation.

What big questions do we still have about dinosaurs?

One of the trickiest issues is how to determine a dinosaur's sex. It has been the focus of many studies but has been found to be more complex than we first thought. Other mysteries include what their behaviour and cognitive abilities would have been like. Living animals are good in these aspects, but there is very little evidence in dinosaurs.

settle the matter. After a long debate, Anning's plesiosaur was confirmed to be legitimate. However, it wasn't a bad idea to take discoveries with a pinch of salt because forgers had already begun to scam museums with fake fossils.

The dawn of palaeontology was an exciting time, but many researchers thought it was too early to be drawing conclusions from such a small record. Others documented all the information they could, but it involved a lot of paperwork. Everything had to be written down, from fossil databases and family trees to painstaking statistical analysis. German palaeontologist Heinrich Georg Bronn was at the forefront of logging dinosaur data. He used innovative methods to represent information that was new at the time, like graphs. He built up a database by studying what fossils looked like and crunching the numbers. The index he published in 1849 demonstrated when certain species appeared and disappeared at different times and was a remarkable breakthrough.

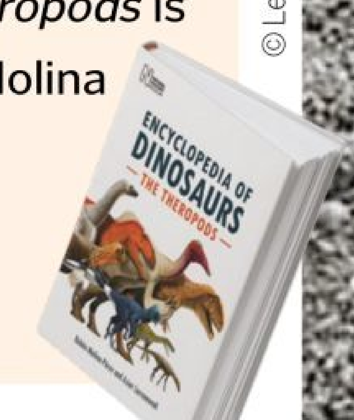
Radioactivity was discovered in 1896, and it wasn't long until it could be used to measure geological time by studying the rate of decay of naturally occurring radioactive isotopes. This helped determine the age of fossil rocks, and by the end of the century scientists had worked out a rough timeline of when these creatures lived. They began to realise the planet was much older than they had previously thought and started to see geological history very differently.

"Forgers had already begun to scam museums with fake fossils"

The invention of computers had a big impact on data analysis, as a lot of information could suddenly be processed by a machine in a short time. Computers transformed the entire discipline of palaeontology. Huge databases have been built online, and computers are able to model the relationship between fossils and life on Earth now. Perhaps most importantly, we can build up images of what dinosaurs looked like using precise imaging techniques. There's a lot we still don't know, but we're making new discoveries all the time.

Learn more

The Encyclopedia Of Dinosaurs: The Theropods is written by Eofauna researchers Rubén Molina and Asier Larramendi and illustrated by Andrey Atuchin and Sante Mazzei. More information at **www.eofauna.com**.



Dinosaur myths and legends

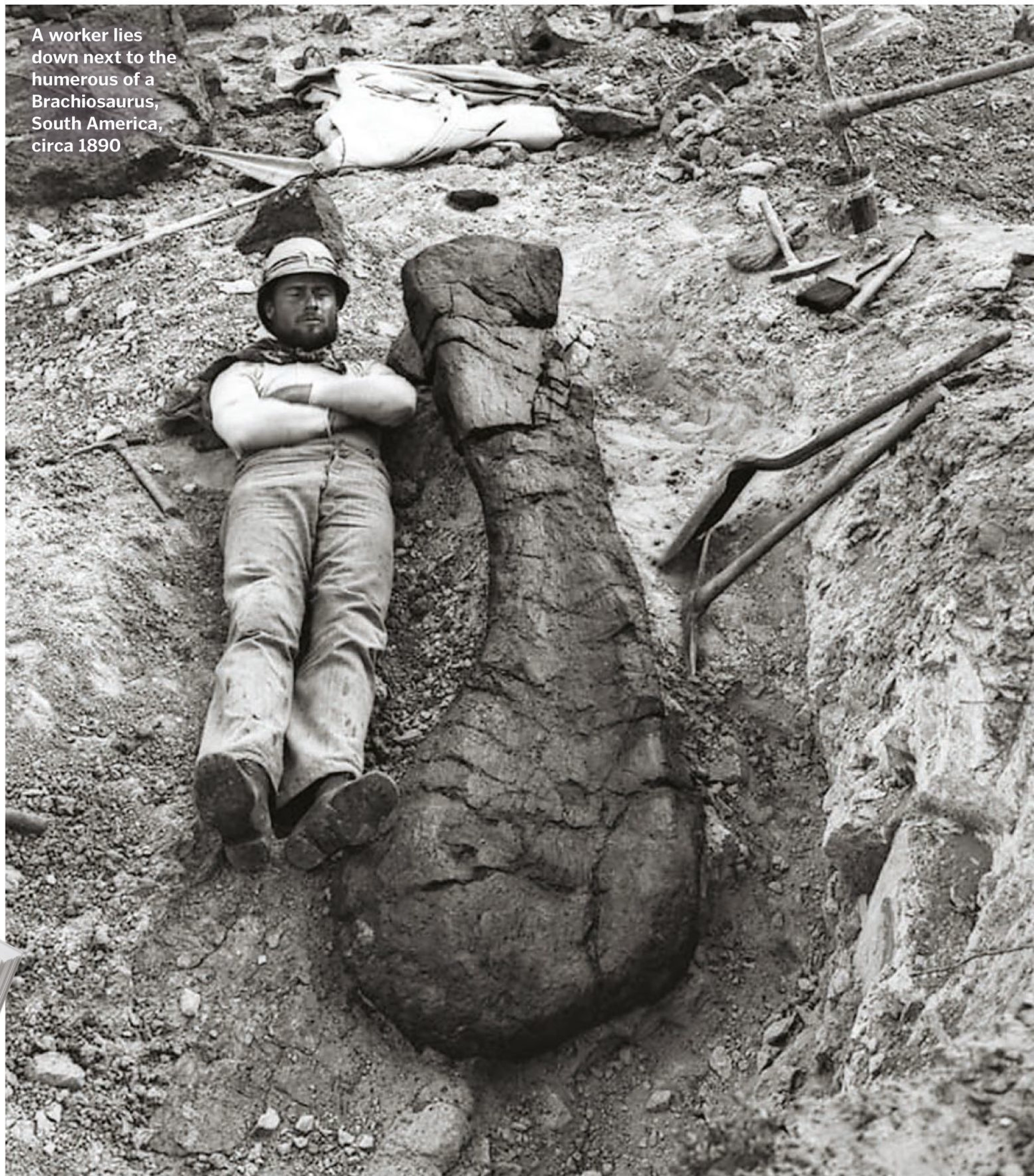
Remains of large, extinct animals have been found throughout history, long before we knew what they were. The enormous bones inspired people to speculate about what bizarre creatures might exist in the vast world around them.

Circular holes in skulls of extinct elephants might have convinced ancient Greeks of the existence of the one-eyed cyclops. It's been suggested that griffins, sphinxes and sea monsters had their origins in fossil remains too.

There's a good chance dinosaur remains also sparked myths about dragons. It would explain why they are part of mythology in so many cultures across the globe and have been for a very long time. Sculptures of dragons in China date back to around 6000 BCE. They were constructed by Neolithic humans and were probably worshipped. Chinese historian Chang Qu wrote about dragon bones in around 300 BCE, but we don't know what animal they really came from.

The eye-shaped opening in an elephant skull is actually where the trunk attaches to the face

© John Cummings



A worker lies down next to the humerous of a Brachiosaurus, South America, circa 1890

© Leon Becker

200 years of dinosaur development

Our understanding of the Iguanodon has changed dramatically over the centuries

1822
The first Iguanodon teeth are found by Mary Ann Mantell and studied by her husband Dr Gideon Mantell. Georges Cuvier states his belief that they may have been from an extinct hippo-like animal.

1825
The fossilised teeth resemble those of an iguana, only many times larger. Mantell names the creature Iguanodon, which means 'iguana tooth'.

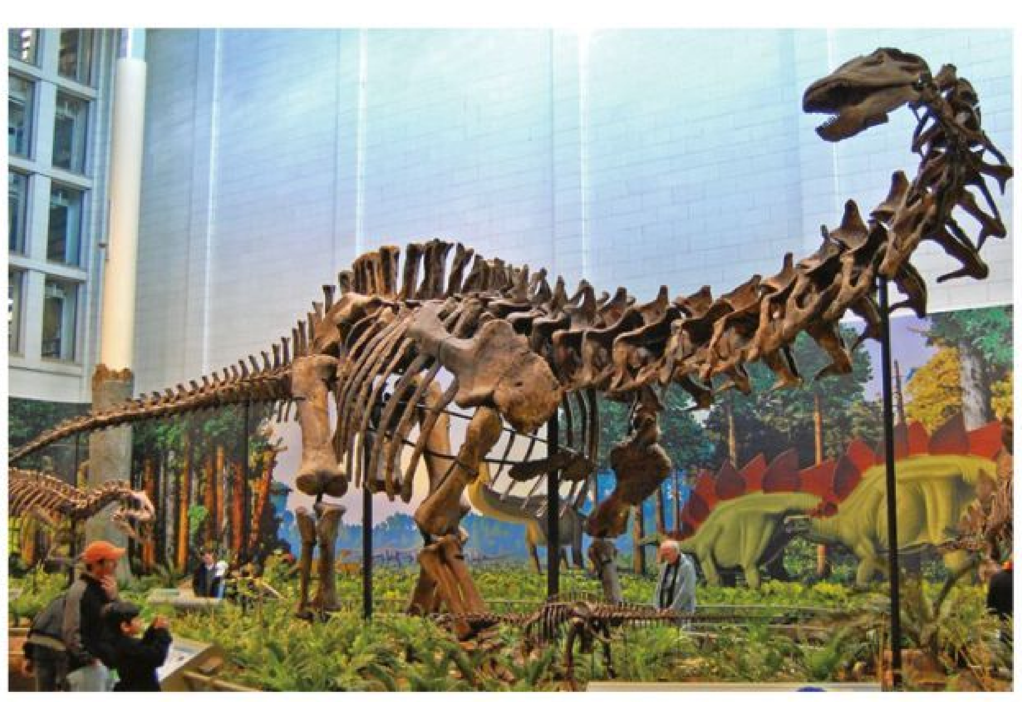
1853
Sir Richard Owen and his associate Benjamin Hawkins reconstruct Iguanodon. They put its spiked thumb on the tip of its nose, believing it to be a horn, with the dinosaur standing on all fours.

1872
The spike is recognised as one of a pair of sharpened digits that protrude from the wrists. They are believed to have been used as weapons that served no other purpose.

1882
Dr Louis Dollo rebuilds an Iguanodon skeleton, modelling it on the modern emu. The new reproduction stands erect on two legs.

1980
Dr David Norman analyses the dinosaur's tail and realises it wasn't flexible, and therefore Iguanodon must have walked on all fours. He also notices its fingers were able to grasp objects.

2005
After studying their footprints we now think Iguanodon was an optional tetrapod able to balance on its back legs. Trace fossils indicate it was around ten metres long.



An Apatosaurus skeleton that was misidentified in 1877 and was corrected in 1903

DINO FACTS

15
Kosmoceratops had 12 more horns than Triceratops

A T. rex had 60 serrated teeth that could be up to 20cm long

700
The number of therapod species we have identified so far

75 cm
Therizinosaurus had the longest claws of any animal ever known

Some think Apatosaurus could break the sound barrier by whipping its tail

THE OLDEST FOSSIL POO IS MORE THAN 200 MILLION YEARS OLD

HERBIVOROUS DINOSAURS ATE ROCKS TO HELP GRIND UP SWALLOWED FOOD

1cm
The length of the smallest, non-avian dinosaur egg (Jinfengopteryx)

WE DON'T KNOW WHY STEGOSAURUS HAD PLATES ALONG ITS BACK ?

1 METRE
The length of a Brachiosaurus foot

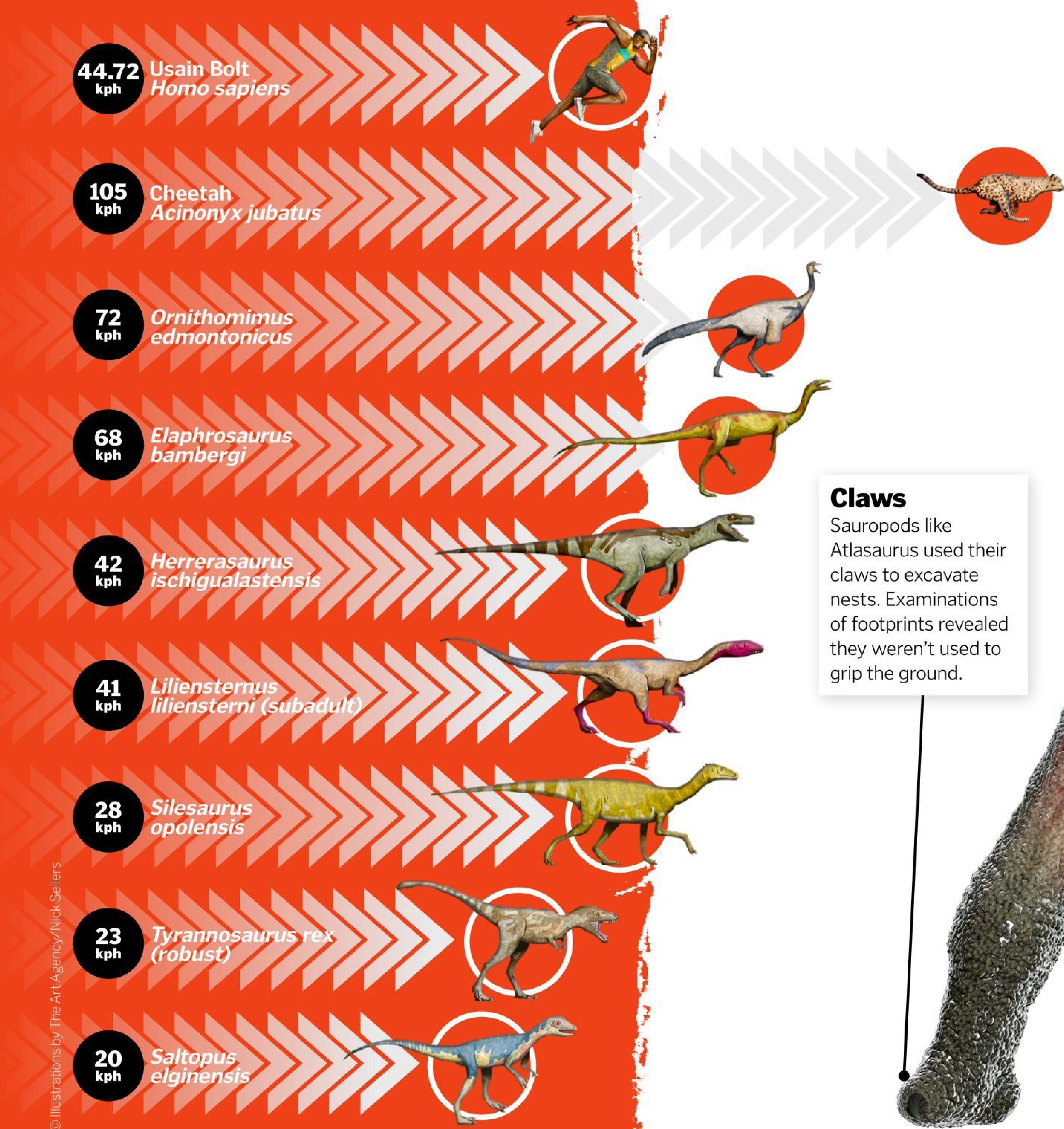
30 YEARS
The typical lifespan of a dinosaur

Champion sprinters

Extinct theropods were seriously quick and a match for fast runners that live today

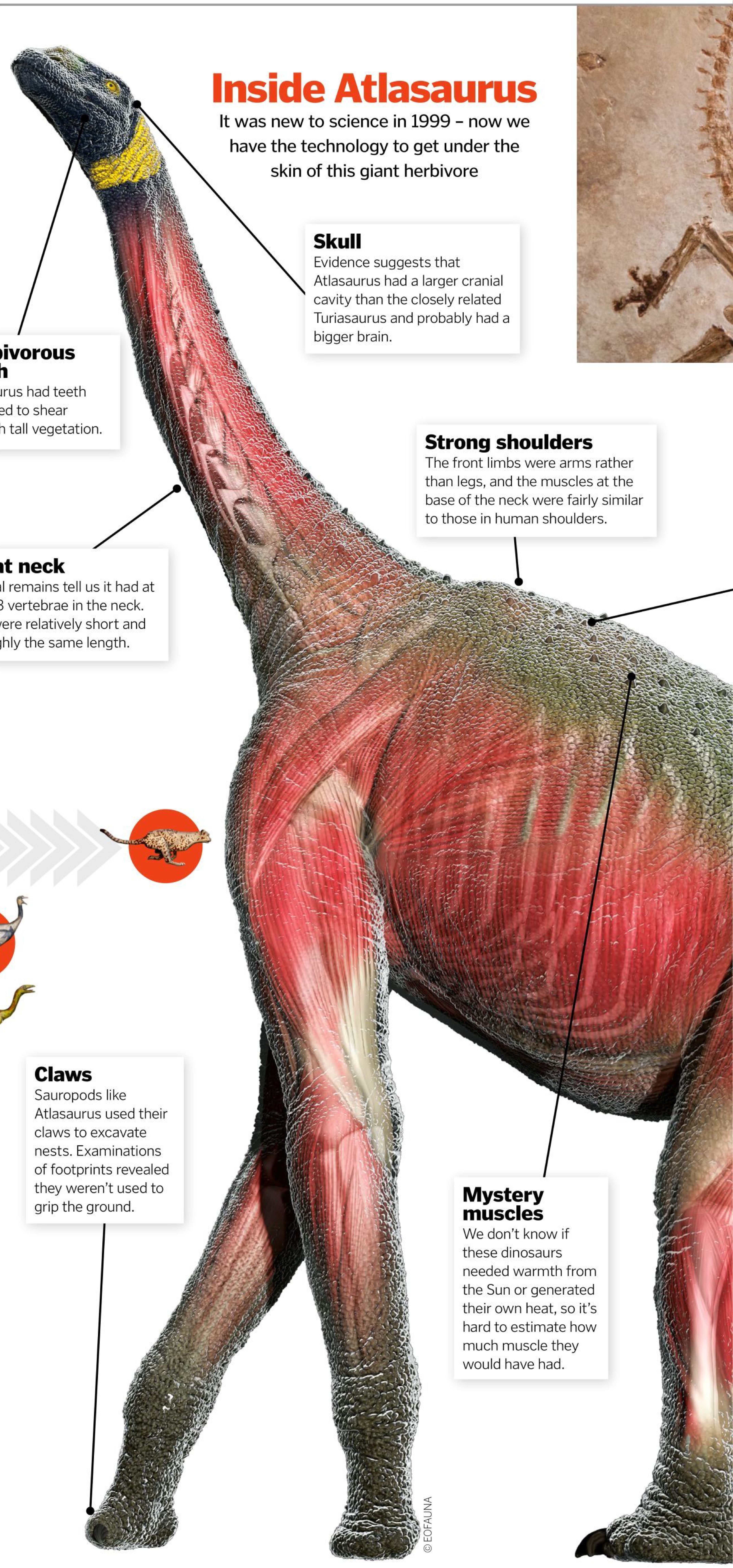
We estimate a dinosaur's speed by considering a number of factors. We look at the length of its strides, how many steps it took per second and the proportions of its leg bones. All of this data is compared to that of modern running birds like ostriches, yielding results that seem logical. The animal's mass also had a significant effect on how fast it could run. T. rex was only as fast as the extant roadrunner because it was so heavy.

An animal well adapted for running is described as cursorial. Estimated values of cursoriality come from body mass, cadence and stride ratio. These numbers are multiplied by the length of the dinosaur's legs to calculate the speed it was capable of reaching.



Inside Atlasaurus

It was new to science in 1999 – now we have the technology to get under the skin of this giant herbivore



Skull
Evidence suggests that Atlasaurus had a larger cranial cavity than the closely related Turiasaurus and probably had a bigger brain.

Herbivorous teeth
Atlasaurus had teeth designed to shear through tall vegetation.

Strong shoulders
The front limbs were arms rather than legs, and the muscles at the base of the neck were fairly similar to those in human shoulders.

Squat neck
Skeletal remains tell us it had at least 13 vertebrae in the neck. They were relatively short and all roughly the same length.

Claws
Sauropods like Atlasaurus used their claws to excavate nests. Examinations of footprints revealed they weren't used to grip the ground.

Mystery muscles
We don't know if these dinosaurs needed warmth from the Sun or generated their own heat, so it's hard to estimate how much muscle they would have had.

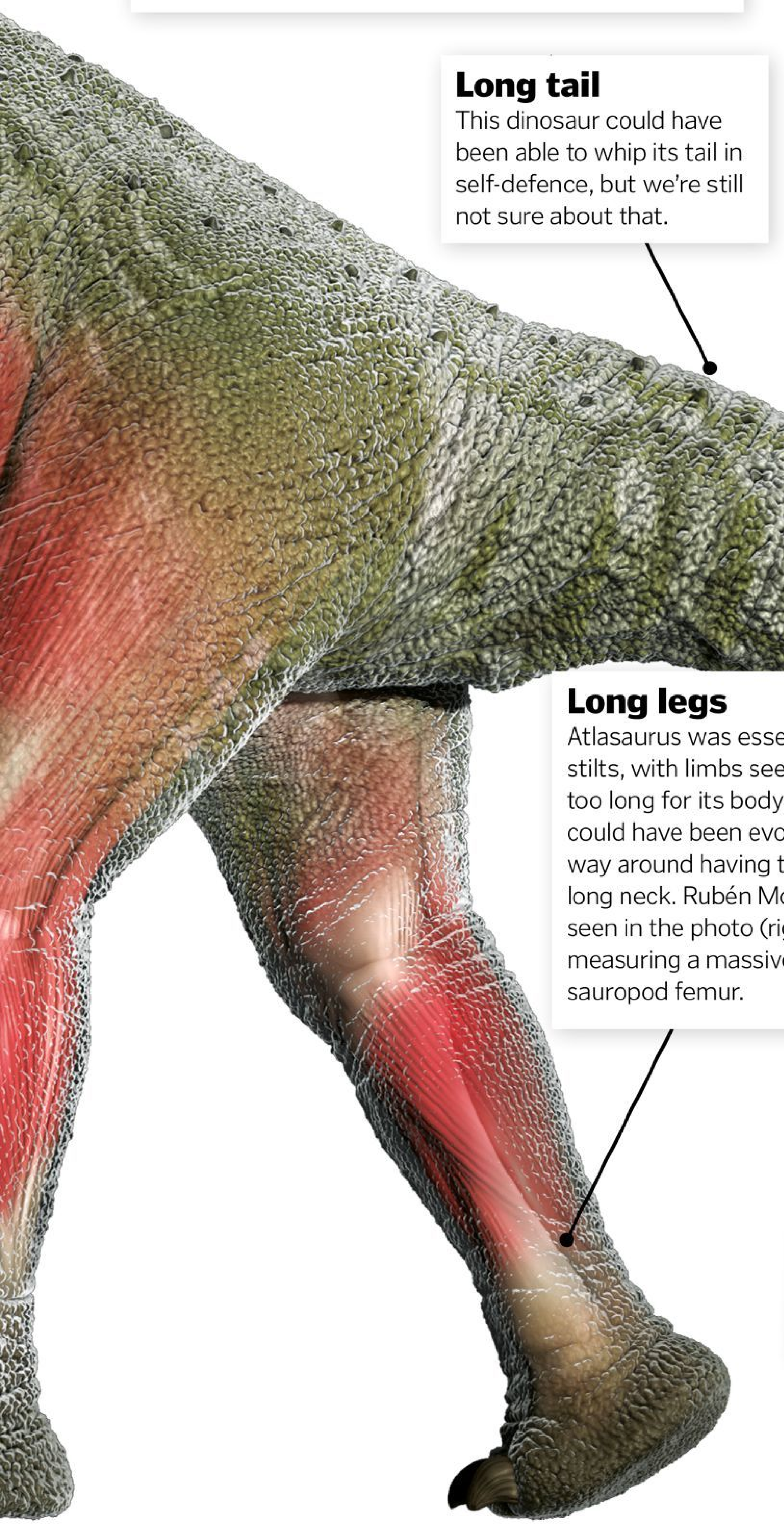
© Getty

The *Sinosauropteryx prima* was the first dinosaur to be found with feathers

Why were the dinosaurs so big?

The niches left by the victims of the Permian extinction 250 million years ago were soon occupied by newly evolved dinosaur species. Dinosaurs could eat fibrous plant matter without chewing it. They could consume a lot in a short time and eventually grew to be enormous. Big dinosaurs also had few predators, so size was selected for by nature.

Reptiles could grow much larger than mammals because of their thicker limb bones and huge cartilages. These shock absorbers reduced stress on the joints, which allowed them to achieve body masses many times that of most large mammals.

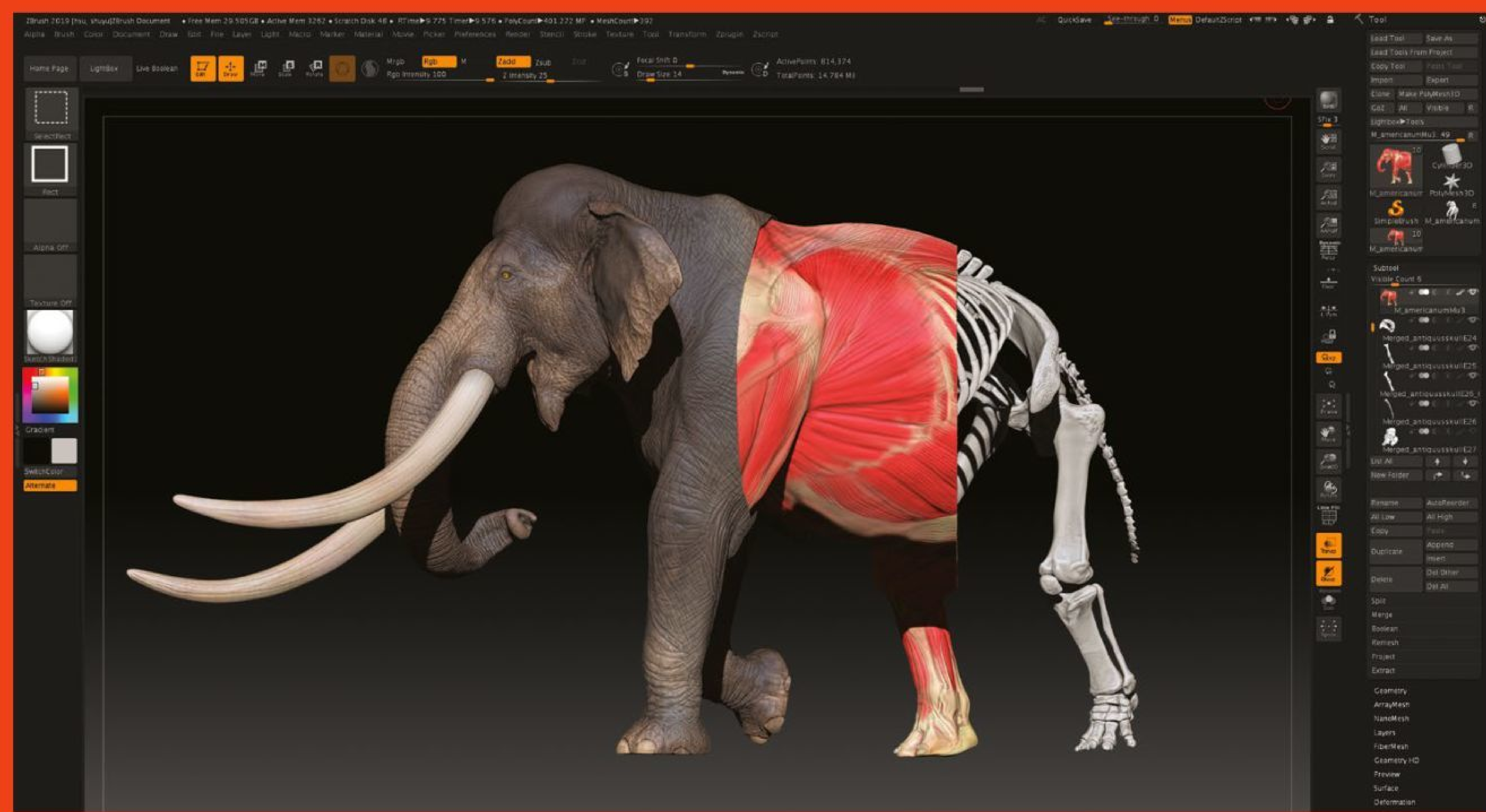


Long tail

This dinosaur could have been able to whip its tail in self-defence, but we're still not sure about that.

Long legs

Atlasaurus was essentially on stilts, with limbs seemingly too long for its body. This could have been evolution's way around having to grow a long neck. Rubén Molina is seen in the photo (right) measuring a massive sauropod femur.



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Bringing extinct animals to life

Eofauna's Asier Larramendi tells us how scientifically accurate prehistoric beasts are reconstructed in 3D

"We first either visit museum collections to take photos and measurements or take information about the best-preserved specimens already published in scientific papers. Once we have the proper documentation, we produce a detailed skeletal reconstruction diagram first to have a precise idea of the proportions of the living animal. It is very important to have a well-rounded understanding of how skeletal elements interconnect, a good knowledge on the muscular system of similar living animals today and how other soft tissues (skin, hair, scales, feathers, etc.) are placed in living organisms. This is what is called comparative anatomy.

From this we create a 3D skeleton. In order to make sure its morphology (size and shape) is accurate, we use a photogrammetry technique: we take a series of photographs of the bones from different angles, then digitally generate a 3D model by comparing characteristics in the images. Once the 3D skeleton model is finished by our sculptor Shu-yu Hsu, we add musculature by comparing the extinct species with modern relatives.

For example, if we are working with an extinct proboscidean (elephants and their relatives), the muscle system of modern elephants can be applied [as per *Palaeoloxodon antiquus* above]. If we are working on a dinosaur, we use living archosaurs (crocodiles and birds).

After this the skin and coverings are added. Sometimes we have very good information on extinct animals' skin and covering, such as hair, scales, filaments or feathers. A great example is the woolly mammoth – some superb frozen specimens have been found. Despite dinosaurs going extinct 66 million years ago, some exceptional specimens have also been found [with soft tissue]. These are useful to create a better representation of the living dinosaurs. Finally, we give dynamic poses (running, walking, etc.) based on skeletal motion ranges and biomechanics."

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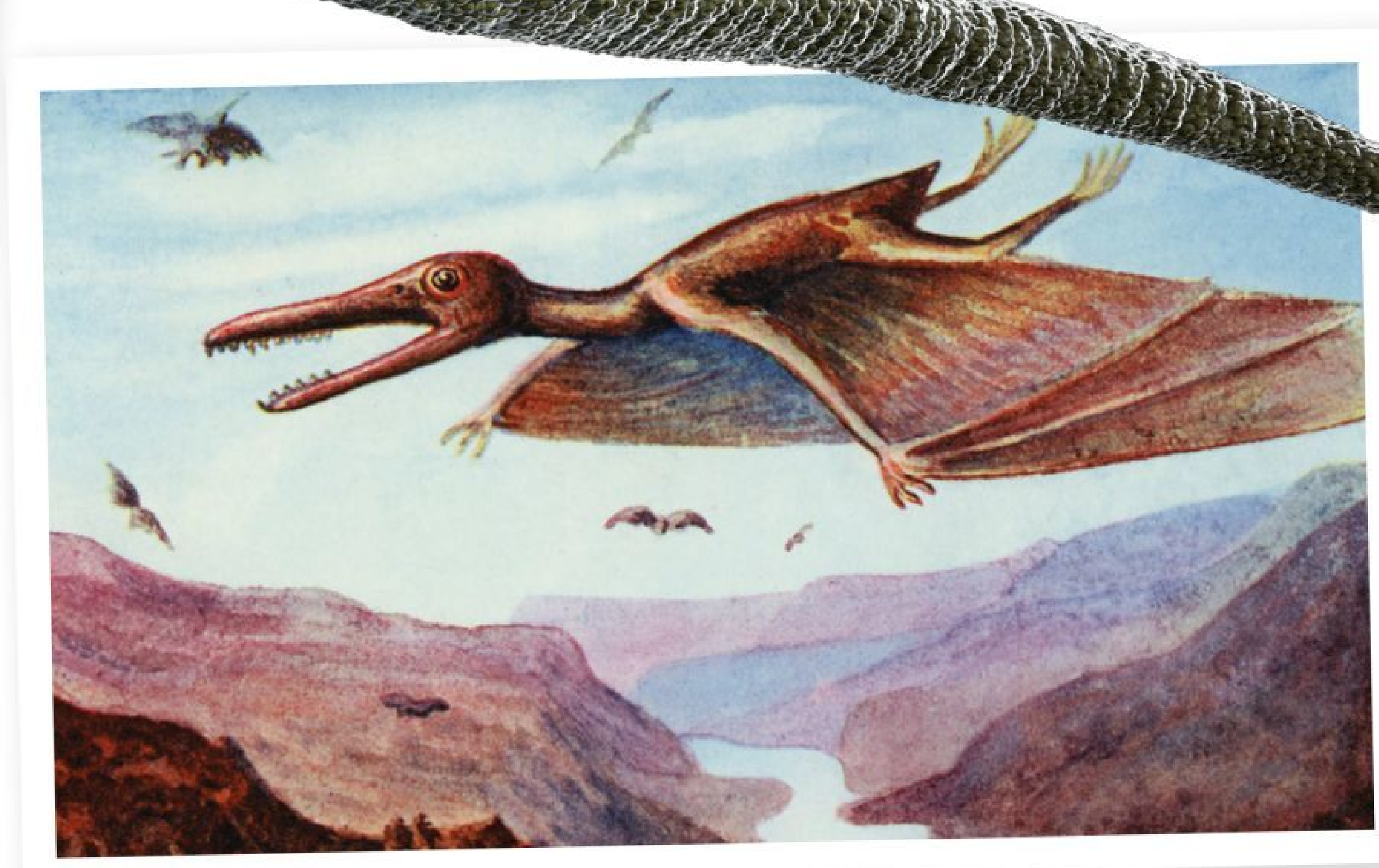

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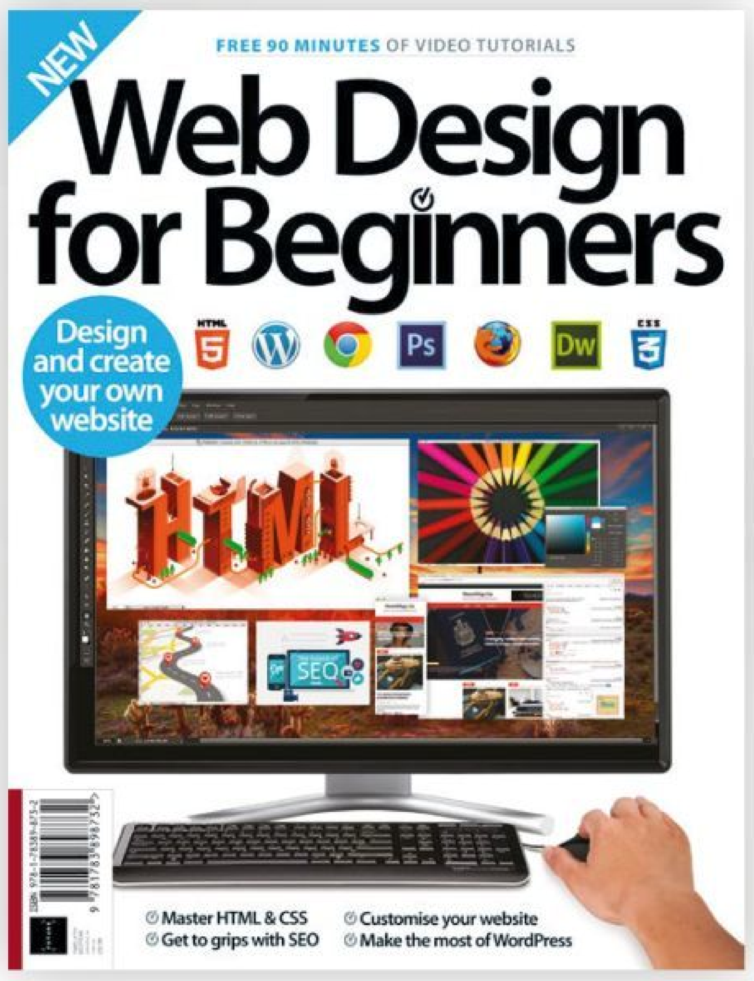
Even though pterosaurs could fly, birds evolved from two-legged carnivorous dinosaurs



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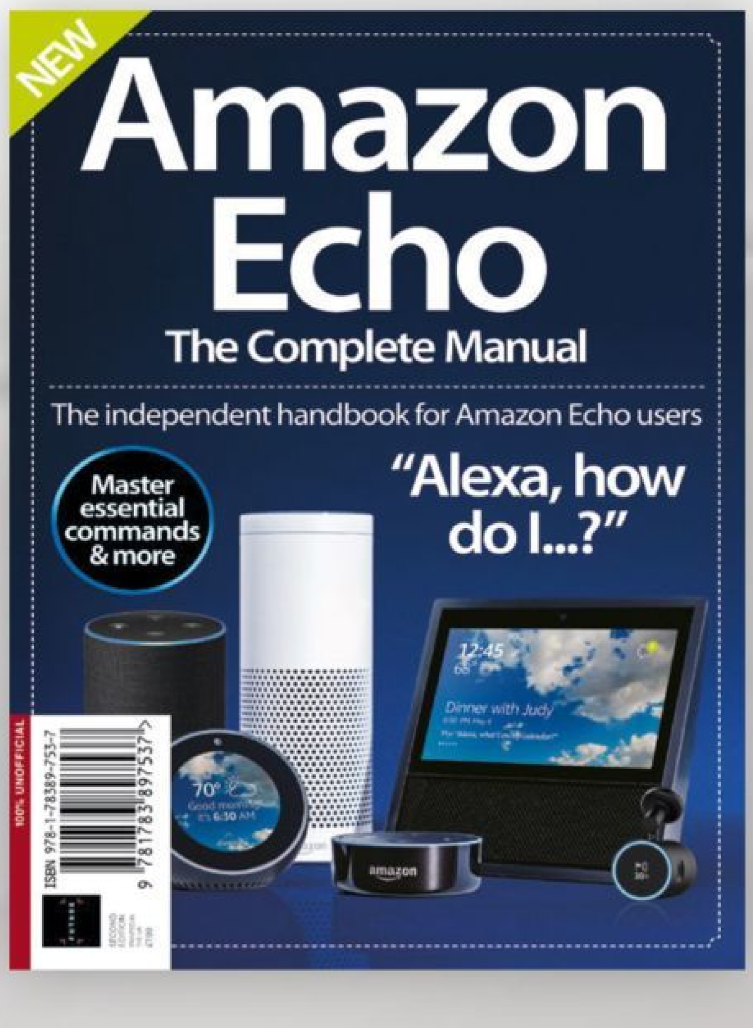
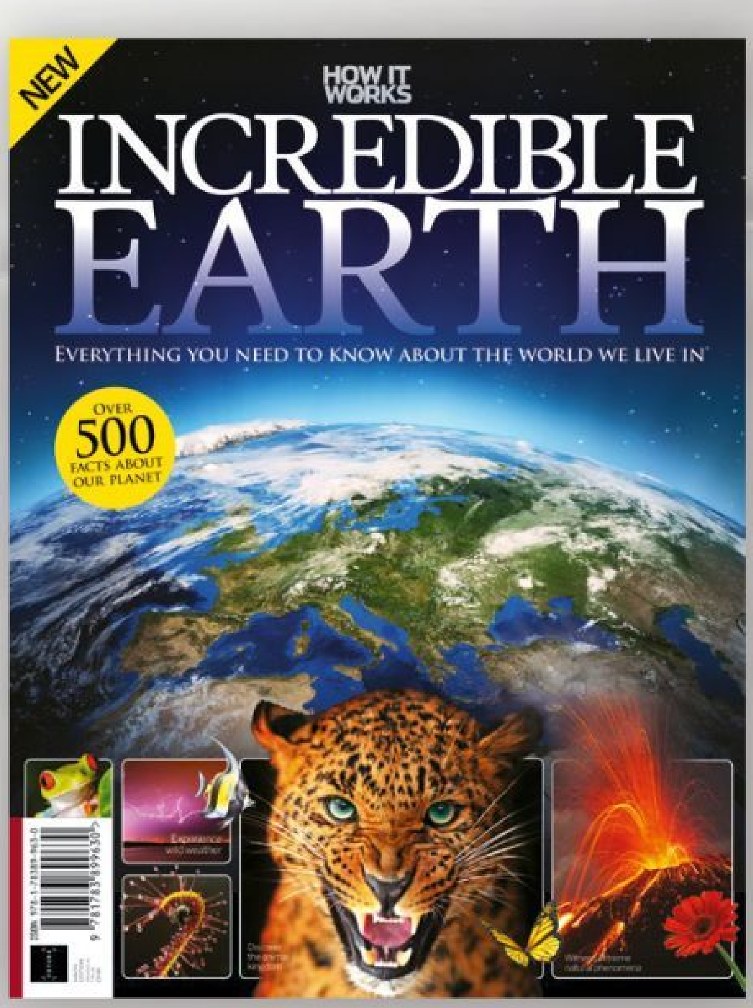
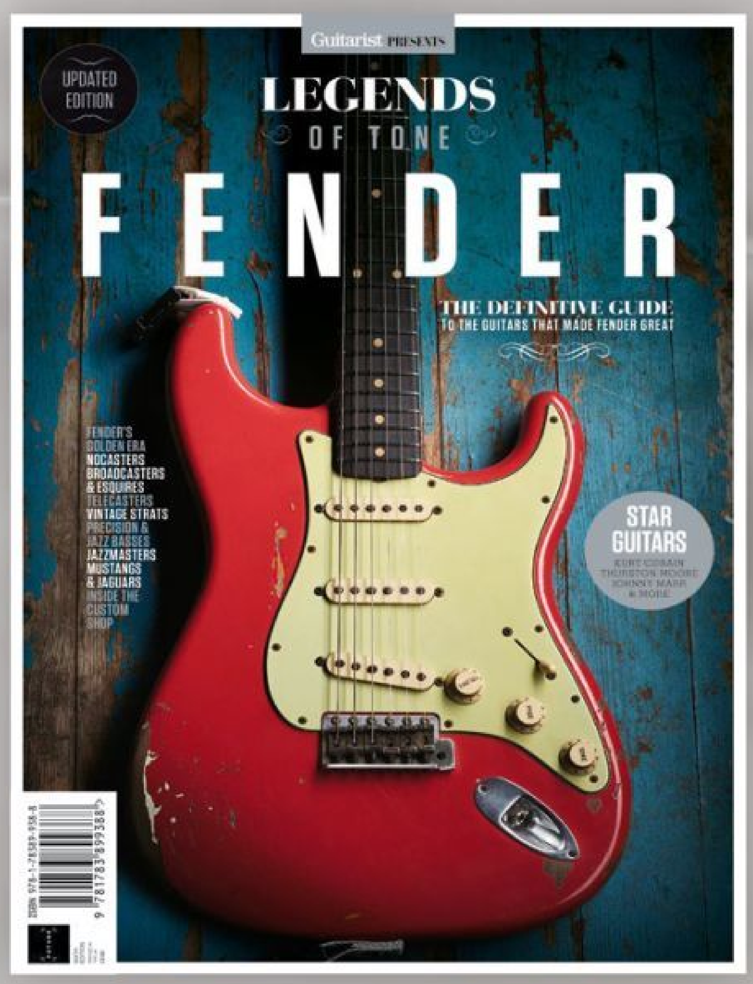
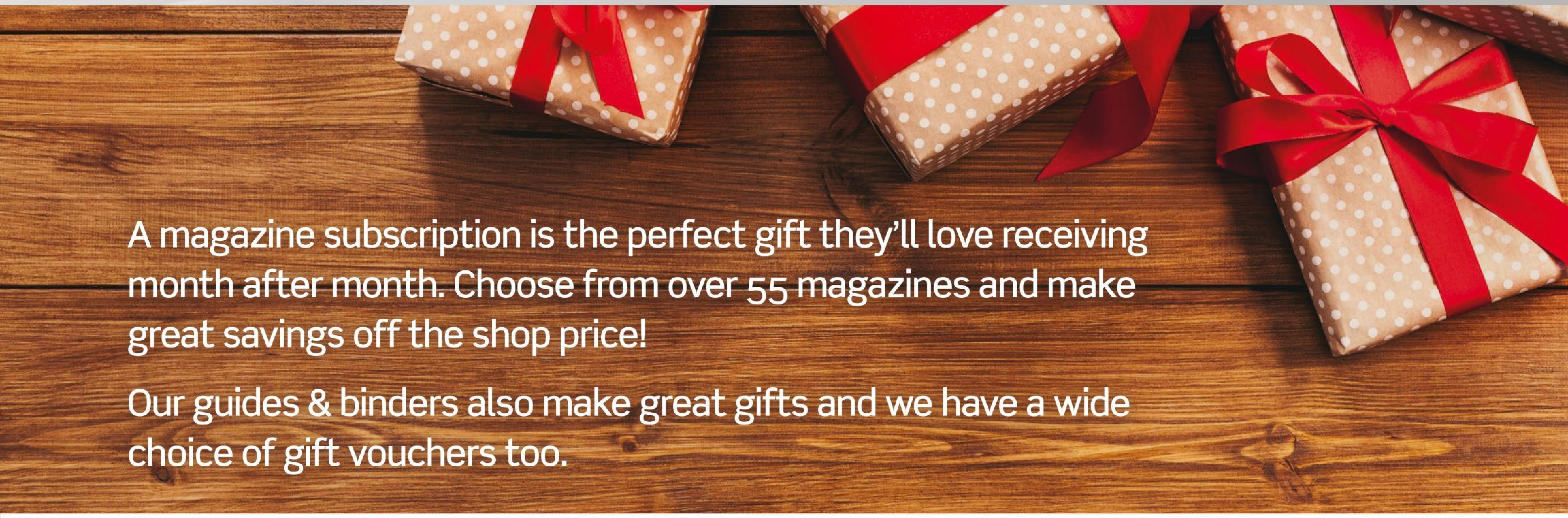
From photography to music and technology to gaming, there's something for everyone.









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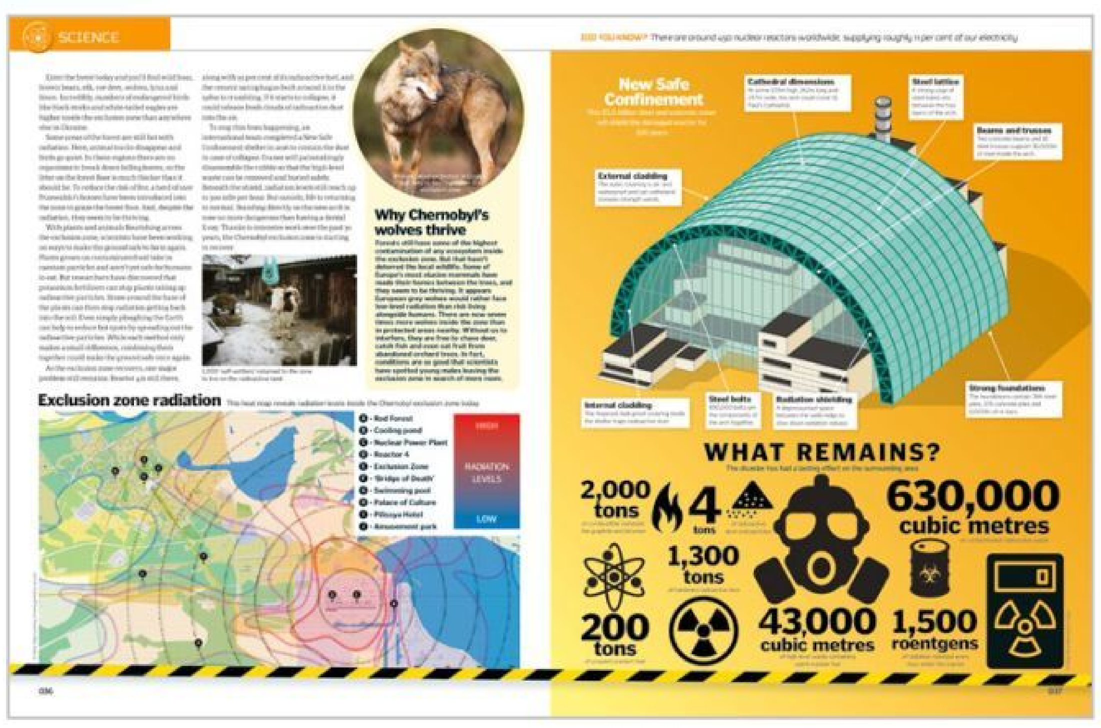


SCIENCE

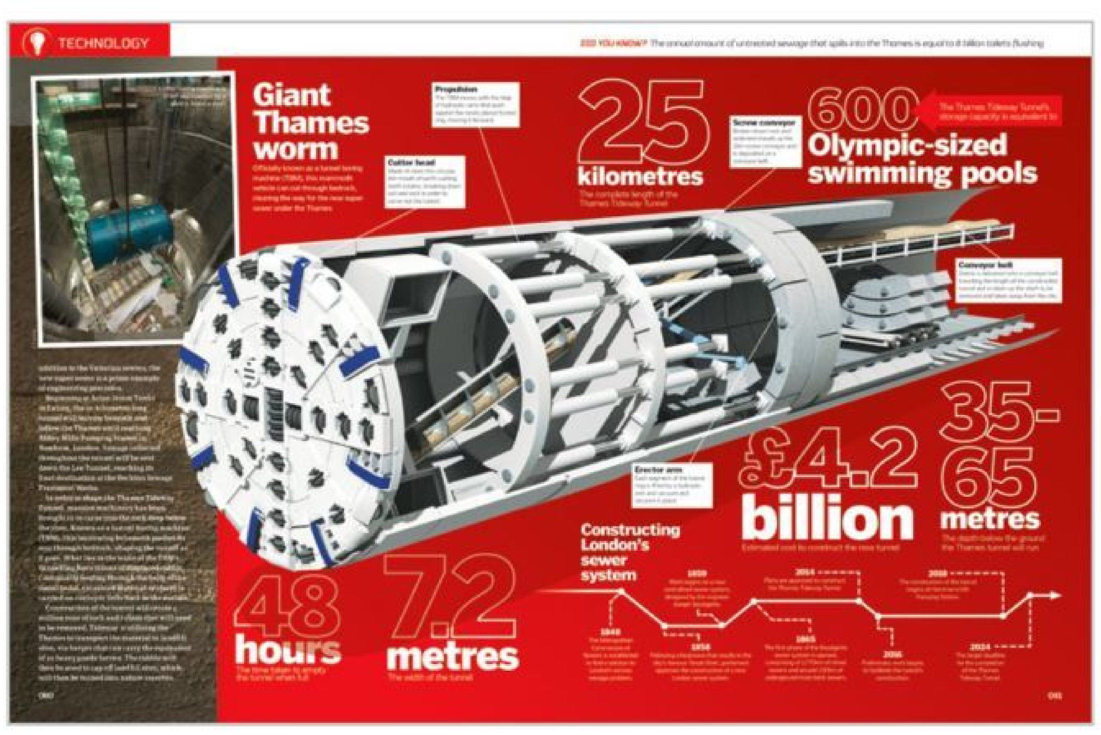
Unearth what really caused the Chernobyl disaster, step into a futuristic operating theatre and explore the make-up of an atom

TRANSPORT

Take to the skies in a Hawk T1 jet, examine the machines set to take over the front lines and find out how cement mixers work

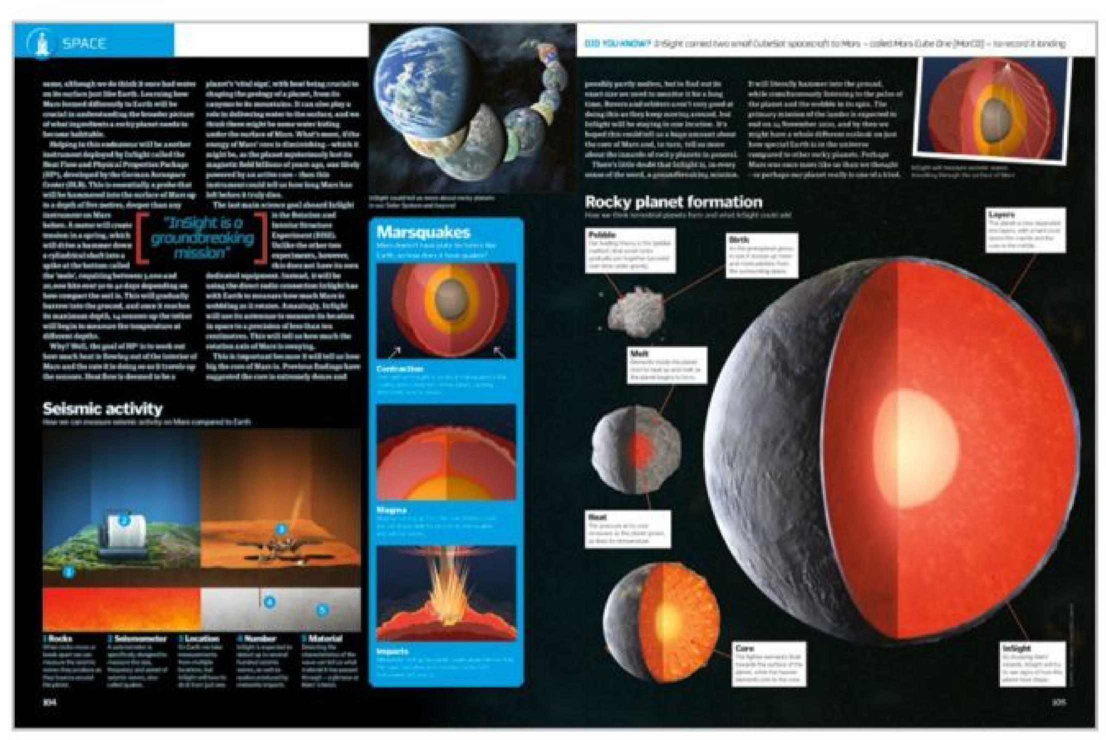
ENVIRONMENT

From hyper-venomous snakes to coma-inducing flora, this annual's environment section is not for the faint-hearted!



TECHNOLOGY

Tour the new super sewer being excavated under London, learn how movie magic is made and meet the man behind the mobile

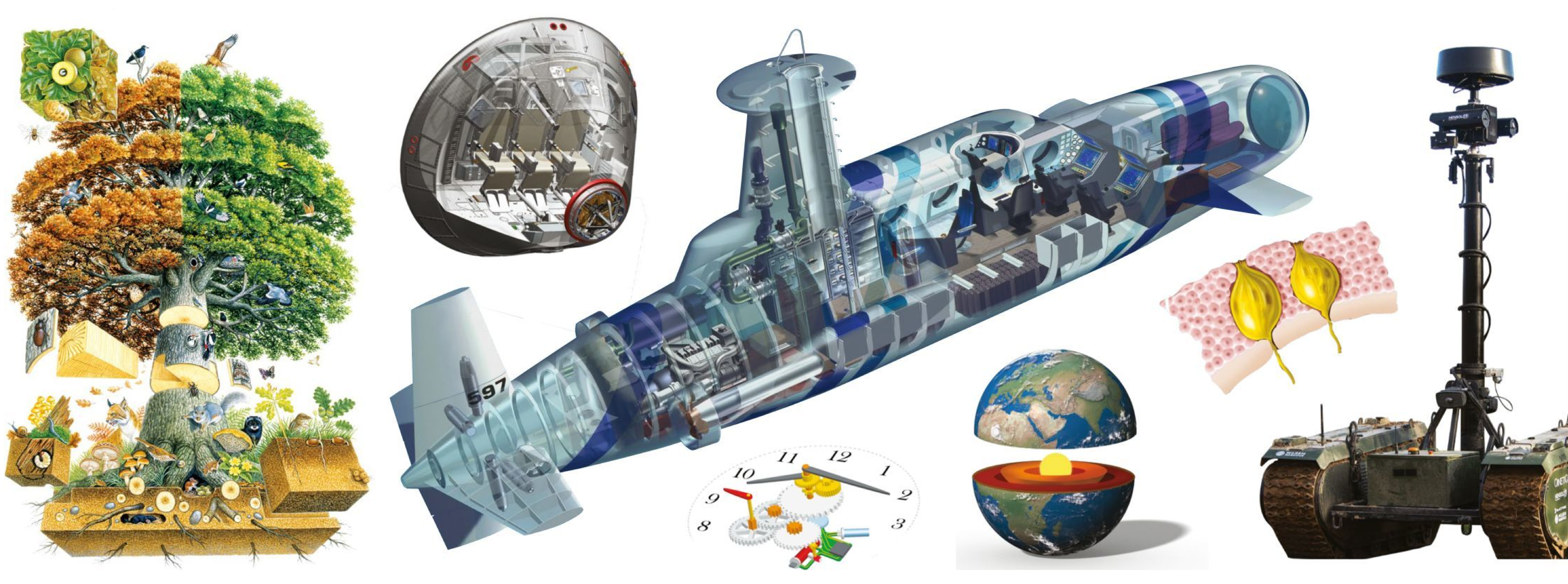


SPACE

Explore the mission to delve into Mars, uncover the secrets of Apollo 11 and discover what happens when two galaxies collide

HISTORY

Get under the shell of a Tiger tank, dig up the frozen fossils of the past and get to grips with some of da Vinci's most ingenious inventions



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